MEMORANDUM NO. 30-4

VIDICON CAMERA AND TAPE RECORDER SYSTEM DEVELOPMENT

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ABSTRACT

A slow scan television camera and a bandwidth-compression magnetic tape recording system are described. These units were especially developed for incorporation into *Juno IIB* as replacements for the originally planned photographic equipment. The performance of the early prototypes along with the engineering philosophy which led to their development is presented in some detail. Work is still being done on the device in order to eliminate the remaining problems which are mostly concerned with the mechanics of the tape recorder and ground recovery equipment.

I. INTRODUCTION

In August, 1958, data received from *Explorer IV* indicated the presence of a high intensity radiation band surrounding the Earth. The level of this radiation was deemed sufficient to severely fog the film in the photographic experiment planned for *Juno IIB*. As a result, a vidicon camera development program was initiated in late August to perform the photographic mission by means of radiation-insensitive techniques. The total effort was divided into two parts, (1) a slow scan television camera and (2) a bandwidth-compression magnetic tape recording system development. The first of these was handled by the Astro-Electronic Products division of the Radio Corporation of America under contract, and the second was initiated at the Jet Propulsion Laboratory. A vidicon and tape sample were immediately subjected to radiation fields in excess of those expected in flight with the results that both samples were functionally unaffected by the environment.

II. VIDICON CAMERA DEVELOPMENT

In addition to the *Juno IIB* environmental requirements, initial specifications on which the vidicon design was based are as follows:

1. Maximum weight: 5.0 lb including high voltage battery supply
2. Pointing angle: 70 deg off axis
3. Minimum video readout time: 2 sec
4. Resolution: 200 lines
5. Exposure time: 1 to 1.5 ms
6. Power consumption: 10 watts maximum
7. Vertical scan synchronized with shutter

A. Vidicon Design

To meet these requirements, an existing design was modified and repackaged. The delivery schedule called for arrival of an operating breadboard unit at JPL by October 1, 1958, a type tested flight unit by November 4, and the remaining five flight-acceptance-tested units at one week intervals thereafter.

A functional block diagram of the R.C.A. slow scan camera unit is shown in Fig. 1. It is conventional in form, and produces a composite video output signal containing mixed horizontal and vertical synchronized pulses. It is unconventional in that all parameters are factory preadjusted and therefore no adjustments other than optical focus are available in the flight package.

The heart of the camera unit, the vidicon, is a cylindrical cathode-ray tube having a photoconductive target. The target structure consists of a transparent, conductive, target electrode which is deposited on the inner surface of a glass face plate followed by a second deposit of photoconductive material. Adjacent to this, a fine wire mesh is mounted.

In operation a positive potential is applied to the target electrode. Electrons arriving in an illuminated target region are drawn toward the target electrode by a high target accelerating voltage (created by the low resistance photoconductive surface) and cause current to flow in the target load circuit. Electrons which arrive in a darkened target area fail to be accelerated toward the target electrode because the surface potential is low as a result of the high-resistance semiconductor path in the unilluminated area. These electrons are consequently collected by the mesh, thus causing no load current. An electrical analogy of a target-surface increment consists of an imperfect photoconducive resistance shunted by an incremental target capacitance. The actual load current results from the discharge of this capacitance. The significant factors which affect tube output current are:

1. Photoconductive surface sensitivity
2. Degree of imperfection of the photo surface (dark resistance)
3. Effective incremental capacitance ("stickiness")
4. Horizontal scan velocity
5. Incident light energy

Because of the low scan rate and highlight-brightness requirements placed on the camera unit, selection of sensitive, "sticky" vidicons having low dark currents became necessary. Since these characteristics cannot be closely controlled in manufacture, suitable tubes could be located only through selection from a large sample.

With the exception of a vacuum-tube video-amplifier input stage, the camera circuitry is fully transistorized. The video amplifier has a voltage gain of approximately 500 and contains a video clipper and dc restorer, sync mixer, and output stage capable of delivering a 2.5 volt composite video signal into a 3900Ω load. Figure 2 illustrates a typical composite video signal. Referring again to Fig. 1, accelerating-anode and focus-electrode voltages are derived from a static inverter supply operating off the basic —25 volt source. The horizontal and

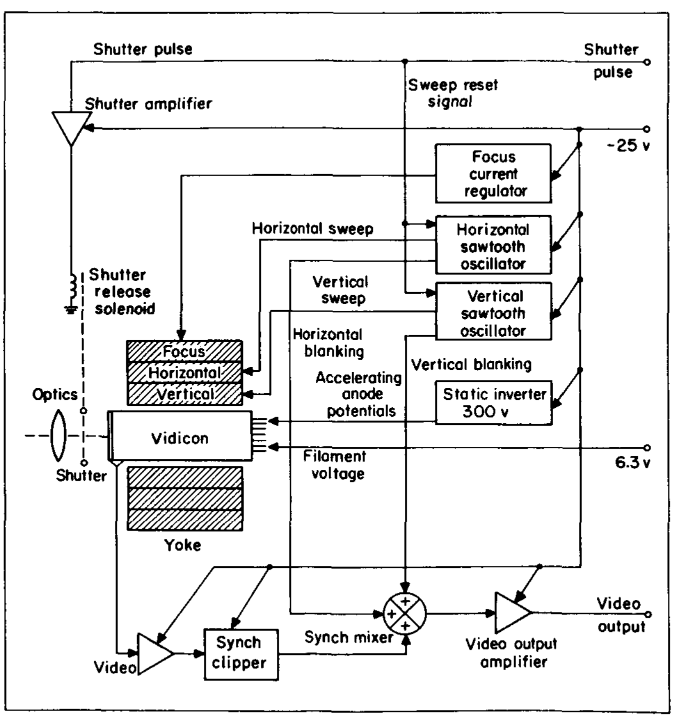


Fig. 1. Vidicon Camera Unit

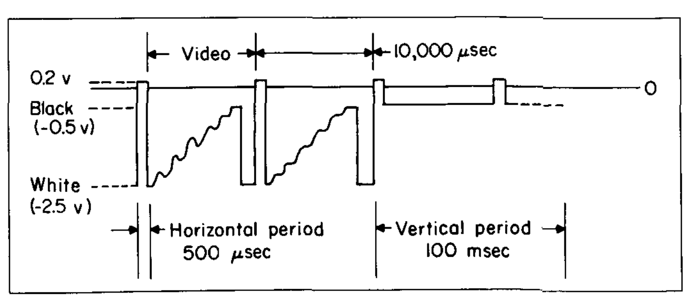


Fig. 2. Typical Composite Video Signal

vertical sweep generators utilize free-running, retrace pulse generators which reset constant-current rate networks to derive the sawtooth signals. These signals are then amplified to drive the horizontal and vertical deflection coils. To satisfy the original specification for synchronization of scans with shutter actuation, a circuit was included on early camera units which reset both sweep circuits by means of the shutter trigger pulse. This requirement was later abandoned when it was discovered that the interrupted-scan mode of operation produced a brightness discontinuity in the picture which was affected by the erasure history of the vidicon. A photograph of this effect is shown in Fig. 3. Auxiliary circuits include a regulated focus-coil current supply, a shutter-solenoid driver amplifier and a horizontal shading circuit. The latter was found to be essential on early units to correct an apparent shading effect on the right half of the picture. Correction was accomplished by introducing the horizontal-sweep signal voltage into the intensity grid circuit to increase the target current over the right-hand portion of the scan. Later investigation showed that this aberration was caused, in part, by a nonlinear horizontal scan rate and subsequent improvement of the sweep circuit provided additional correction.

Fig. 3. Brightness Discontinuity Due to Interrupted Scan Operation

B. Transmission Experiments

An important consideration of system philosophy centers around the quality of picture to be obtained from a communication channel containing noise. Some indication of the picture quality at anticipated signal-to-noise ratios might be gained from Fig. 4, which shows a composite signal of video information and white noise, band-limited to twice the information rate, at a signal-to-noise ratio of 2:1. The picture quality can be significantly improved by averaging out the random-noise components, as is shown in Figs. 5 and 6. Some idea of the types of images actually to be transmitted and the effect of noise on them may be gained from Figs. 7 and 8, which are photographs of a Lunar crater subjected to the same signal-to-noise ratios as before.

These experiments indicated that it is better to transmit one image as many times as possible rather than to attempt recovery of many images.

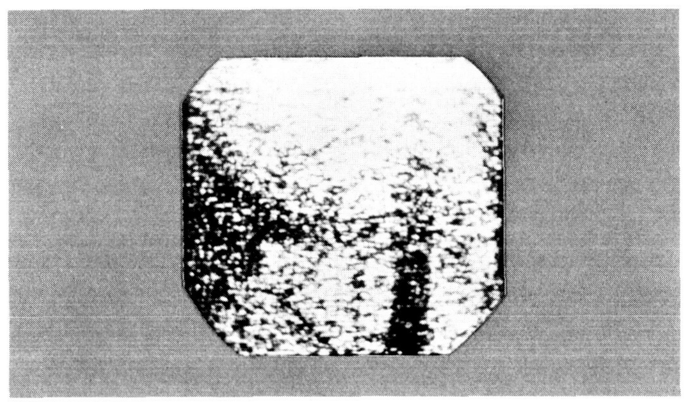


Fig. 4. Single Transmission of Composite Video and White Noise

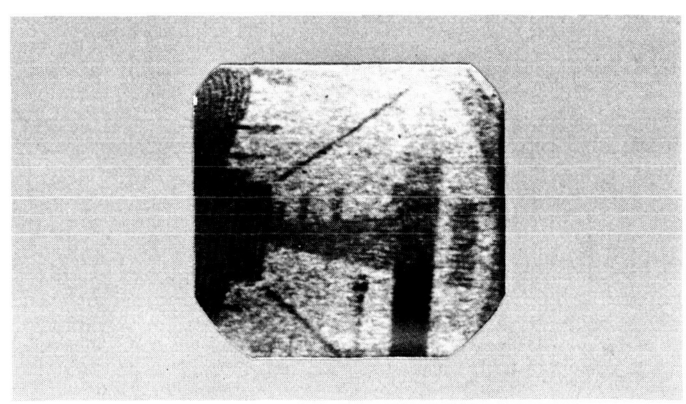


Fig. 5. Random Noise Reduction by Repeated Transmissions of a Single Picture, 25 Averages

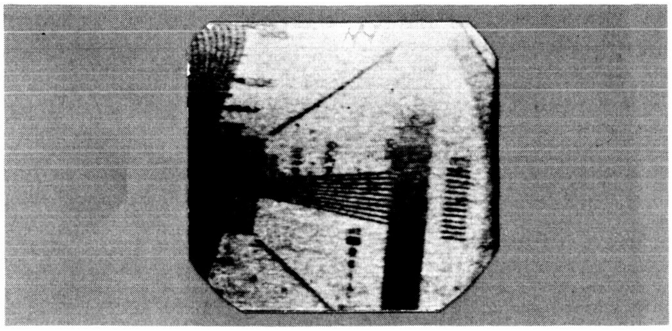


Fig. 6. Random Noise Reduction by Repeated Transmissions of a Single Picture, 50 Averages

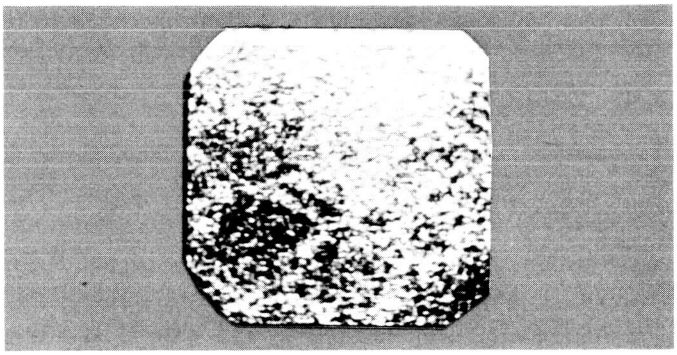


Fig. 7. Lunar Crater; Single Transmission

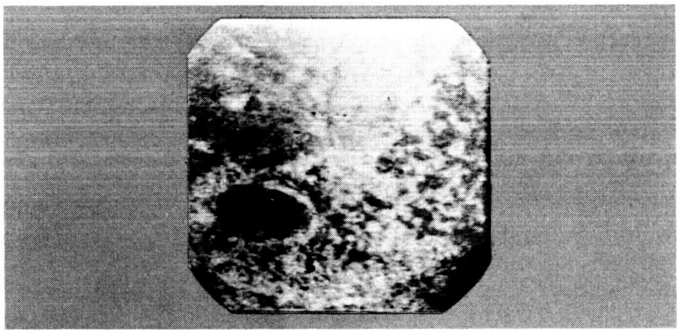


Fig. 8. Lunar Crater; 50 Transmissions

III. TAPE RECORDER DEVELOPMENT

At the inception of the program a set of functional requirements for the tape deck was established. These included:

1. Video system switching to accomplish the following operations with minimum power consumption.
   (a) Two Earth pictures, 50 min after injection, with 20 replays.
   (b) Two Moon pictures, 33 hr after injection, with 40 replays.
2. Reception and storage of video signals having a 10-cps to 10-kc spectrum.
3. Retransmission of the video signal at a compressed bandwidth of 0.01-cps to 10-cps.

Midway in the program a change in these specifications occurred which called for a two-frame single exposure of the Moon, and for the removal of the Earth-picture requirement. Upon re-evaluation of the data-transmission link, a reduction in the upper bandwidth limit from 10 cps to 2 cps was found necessary.

To satisfy these requirements, efforts were initiated to concurrently develop a record-playback technique with appropriate control electronics, and a tape transport mechanism integrated into a compatible structural package.

A. Recording Technique Considerations

Initial record-playback system experiments revolved about the use of a direct flux-responsive recording technique for applying video to tape. High information packing density, a capability of this system, was the basic reason for its consideration.

1. Flux-Responsive System. Several commercially available playback heads of the flux-modulator type were obtained and compatible circuitry was developed for their evaluation. Early results of these tests were unsatisfactory, and an investigation was undertaken to effect a better understanding of their operation. The principal difficulties encountered were an apparent incapability to resolve short recorded wavelengths plus an inherently high output noise content.

Further testing revealed that the response of the flux-reading head was primarily determined by its pole-piece configuration. Response fell off at essentially 6 db/octave at wavelengths on either side of the longitudinal pole-piece dimension. Because of the high output noise level, resolution beyond 30 cyc/in. was undetectable. A reinvestigation of the literature indicated that in all existing applications, moving tape is employed, and that the falling response of the flux-responsive mode is offset by the rising characteristic of the normal $d\phi/dt$ mode. A further difficulty encountered with this type of head was its exceptional response to the Earth's magnetic field, whose level is 3 to 10 times greater than that derived from saturated tape. This was a decided shortcoming for applications in a spinning vehicle.

To alleviate these problems, a record-playback head development program was undertaken independently. The resulting design attacked observed problems by means of a unique construction. A homogeneous magnetic-bridge configuration was adopted to minimize the required volume of saturated material and thereby reduce saturating-power levels and output noise. A photograph of this structure is shown in Fig. 9. Through the use of this homogeneous construction, the back-gap bridge balance is achieved by precision machining rather than by delicate assembly, and saturation-power requirements are thus minimized. The construction is that of a single shim whose thickness was chosen in order to place the front pole-piece longitudinal dimension at the geometric mean of the desired wavelength spectrum. To reduce the effect of the Earth's field, a close-fitting magnetic shield encased the assembly exposing only the pole faces.

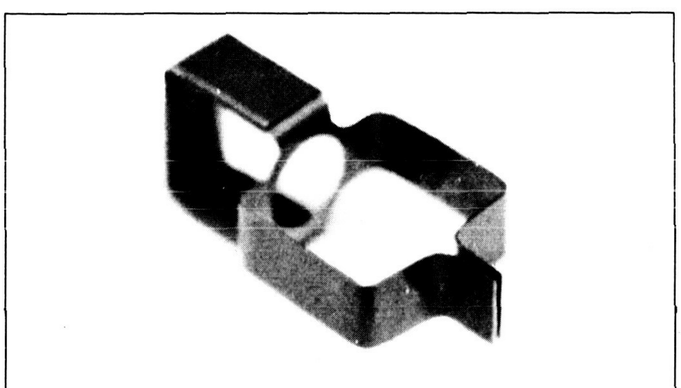


Fig. 9. Magnetic Configuration of Experimental Flux-Responsive Head

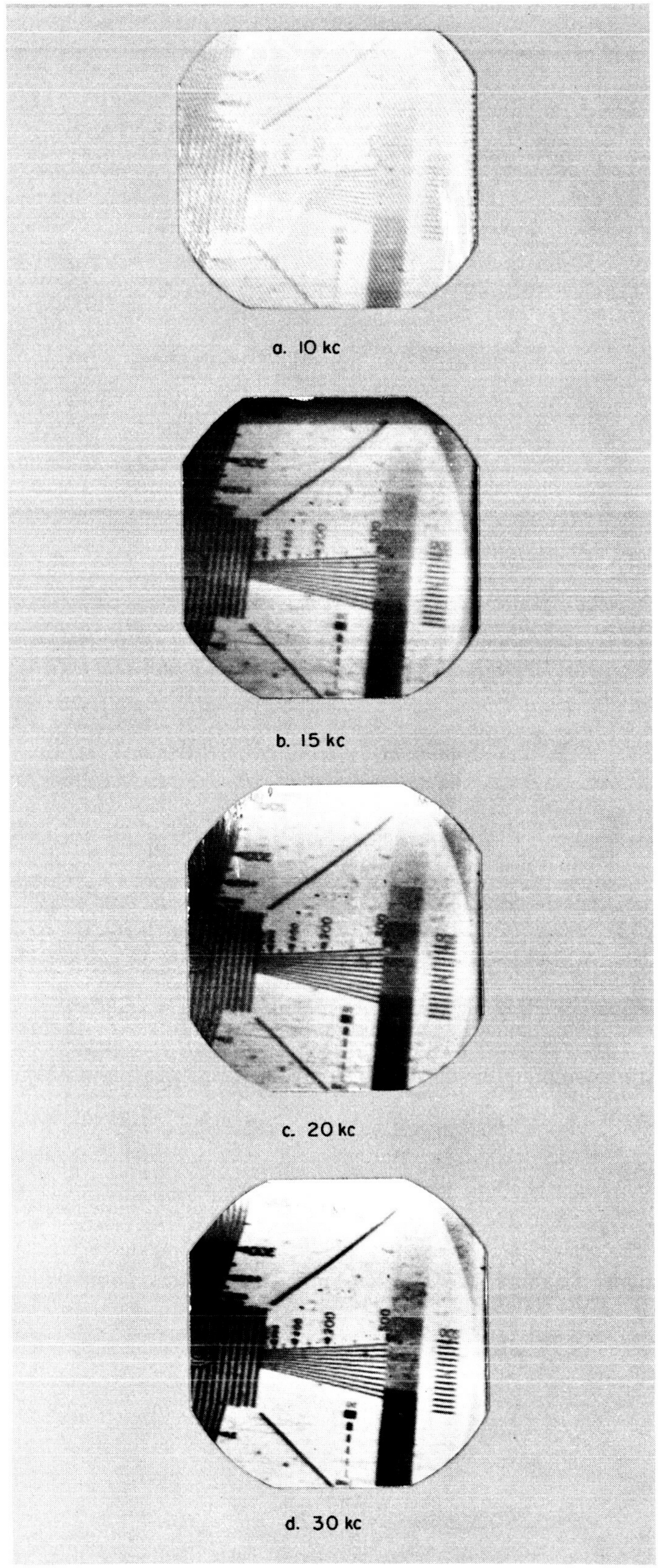
Greater resolution and lower noise content were exhibited, as determined by tests on the completed head. Response to the Earth's field was reduced but remained excessive. Continued testing revealed indications that local pole face or case residual accumulated causing unrepeatable test results. Although it was felt that significant improvements had been achieved, lack of time prevented further development.

2. *Carrier Systems.* As a backup effort for the flux-responsive system development, an investigation of carrier modulation techniques was initiated. For these, two alternatives were presented: (1) a carrier, amplitude modulated by video, and (2) a frequency modulation (FM) system.

The video information to be recorded on tape encompasses a ten octave frequency range with an upper limit of approximately 10,000 cps. The modulation spectrum of such a signal would extend over a frequency range of at least eleven octaves for a minimum carrier frequency equal to the highest modulation frequency. This range is virtually impossible to recover by any present playback technique without serious sideband distortion. For this reason a technique of vestigial sideband modulation was inevitable if standard record-playback magnetic heads were to be used.

a. Amplitude Modulation (AM). The first technique of amplitude modulating a carrier was initiated by constructing a single-transistor equivalent of a De Bijl modulator. Experiments were conducted to determine the minimum carrier frequency for adequate video information. Five carrier frequencies: 10 kc, 15 kc, 20 kc, 30 kc, 50 kc, were chosen. The results of these tests are shown in Fig. 10. Note that the carrier frequency was not filtered in order that the precise information capability might be evaluated. Based upon this test it was determined that a carrier frequency of 20 kc was adequate for a 200 x 200 line image. Actual picture information of a detected AM signal is illustrated by the reproduction of the lunar prominence, Copernicus, shown in Fig. 11. The limiting factor of resolution in these oscillographs is that of the monitor-kinescope focus.

To achieve simplification, an AM technique known as "carrier erase" modulation was investigated. Whereas a standard AM scheme requires a separate oscillator, modulator, and magnetic recording amplifier with ac bias; it was reasoned that the carrier may first be impressed



a. 10 kc

b. 15 kc

c. 20 kc

d. 30 kc

Fig. 10. Demodulated AM Video with Carrier

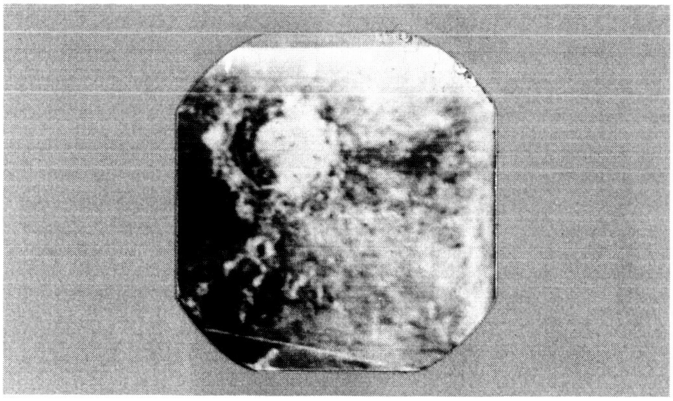


Fig. 11. Copernicus, Using AM System with Unfiltered 30-kc Carrier

separately upon the magnetic tape, thus serving as its own bias. The video could then be "dc" recorded on top of this carrier with a dc magnetizing current. (Fig. 12)

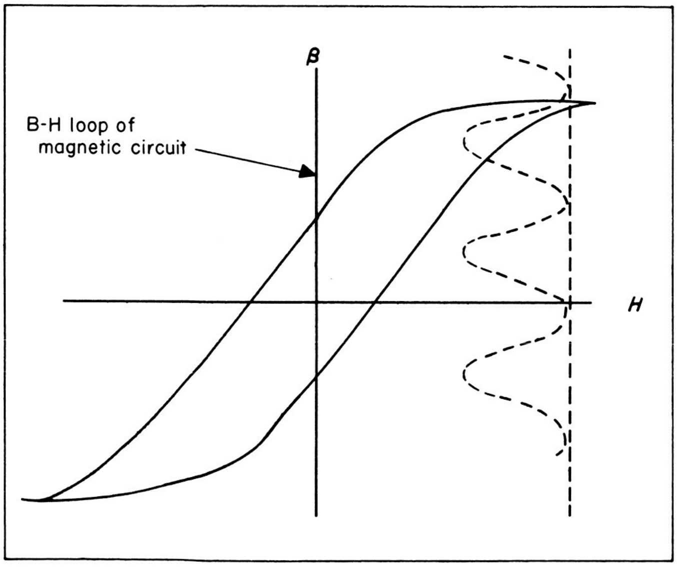


Fig. 12. Graphical Analysis of Carrier Erase Process

The essence of this technique is that the original recording of the carrier is partially erased in accordance with the level of the video signal, thus achieving amplitude modulation of the carrier. The simplicity of this technique may be noted by the fact that, for a prerecorded carrier on the tape, no electronics are required between vidicon output and the magnetic recording head—the vidicon supplying both the proper video current and dc bias. Fig. 13 shows the results of using this process with a 15-kc carrier which was prerecorded at 15 in./sec on an Ampex "300" recorder. The demodulated signal recovered from the tape demonstrates two important conclusions: (1) The recovered video is not degraded in spectrum over the experimental results shown in Fig. 10(b). (2) The wow, flutter, and speed drift characteristics of a standard instrumentation recorder are such as to degrade picture quality even in a noise-free environment.

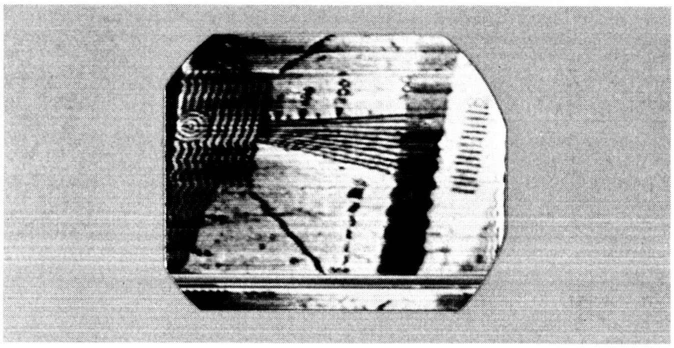


Fig. 13. Carrier Erase Technique Through Ampex Recorder

To assess the feasibility of rapid-record and slow-playback of an amplitude modulated signal, the video was "carrier-erase" recorded at 15 in./sec and (1) played back at 15 in./sec to demonstrate the impression on the tape (shown in Fig. 14); and (2) played back at 0.01 in./sec (shown in Fig. 15). It is observed that severe amplitude noise is introduced at the slow playback speed.

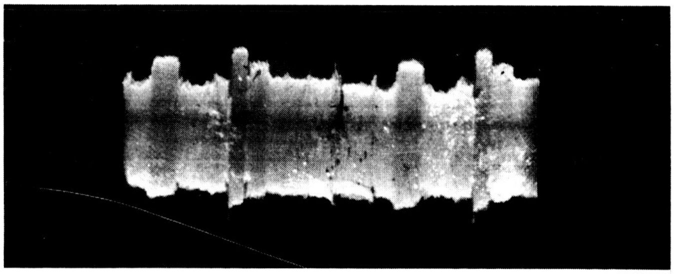


Fig. 14. Modulation Pattern of Carrier Erase System

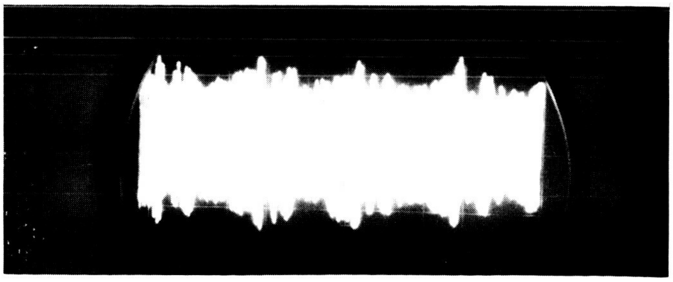


Fig. 15. Slow-Speed Playback of Carrier Erase System

In conclusion, for the amplitude modulation of video we have a recording system of unquestioned simplicity if we prerecord a carrier at saturation level. Furthermore, the detection process involves a relatively simple task of amplifying and filtering since the choice of carrier frequency and tape packing-density yields a vestigial sideband signal which consists primarily of the carrier and video information directly. For multiple recording, the prerecorded, saturated carrier serves as an erase signal as well as a bias, thus obviating any specialized erasure techniques. As a disadvantage, AM signals are seriously degraded by amplitude noise of electronic circuitry as well as noise and "drop-outs" on the magnetic tape. Furthermore, a completely linear playback system is required, thus necessitating careful control of tape-to-head contact for a uniform signal level.

(b) FM carrier system. Concurrent with the AM modulation development, an investigation of an FM recording system was undertaken. The apparent functional simplicity of such a system seemed desirable in that no recording bias or erasure signal is required. Its comparative insensitivity to recorded signal-amplitude variations caused by flutter, tape-to-head contact and tape nonuniformities was regarded as a further advantage. Speed control, a requirement for FM, was not considered an added complication since it was also a requirement in the probe-to-ground video synchronization scheme.

Initial tests were designed to determine the lowest frequency of deviation which could produce reliable output under saturated tape conditions. As a part of these tests, optimization curves of playback signal vs recording current vs packing density were made using several samples of commercially available tapes. These curves are shown for high-output 1-mil acetate tape in Fig. 16. It was concluded that acceptable playback levels could be obtained at a frequency of 5 cps where packing densities did not exceed 500 to 750 cyc/in.

Applying these conclusions, a sample FM system was designed and tested to evaluate picture quality. The test consisted of modulating 10-kc video over a two-to-one deviation about a 22-kc carrier, committing to tape, and restoring through a 22-kc discriminator. The initial results were quite noisy but were considerably improved by the placement of restrictive filtering on the playback carrier signal. The remaining noise was attributed to tape wow and flutter which was uncontrolled during the test.

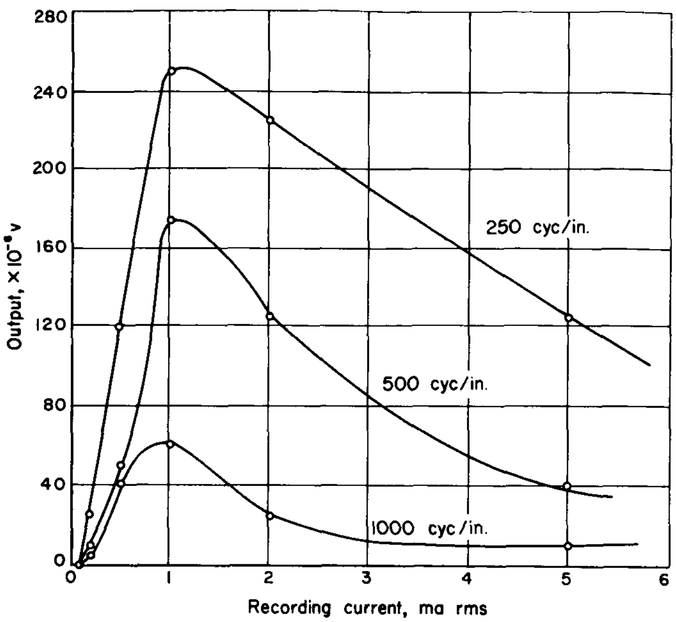


Fig. 16. Optimization Curves for High-Output Tape with Dyna-mu Head

B. Initial Tape Transport Development

The mechanical specifications for the tape transport mechanism were dictated primarily by the recording system and control mode requirements. Tape storage requirements based on the anticipated application of a flux-responsive recording system with a two frame capacity, set the minimum tape length at 40 inches. Record time, governed by vidicon performance, was optimized at the rate of ½ frame/sec. Playback time, controlled by communication system requirements, was set at approximately one frame/hr. As a result of these two stipulations, the record-playback speed ratio became 1800:1. Original control mode requirements, calling for two Earth and two Moon exposures, were later relaxed to provide for one double-scan Moon exposure. Both specifications stipulated a multiple replay feature, although the earlier system required interruption of the Earth-replay sequence at 27 hours with a subsequent transport reset for the Moon sequence.

Mechanization of these requirements was based on the use of a Neg'ator spring motor as the motive force for the record mode. A further system refinement was the concept of using the spring as a base material for the recording process. A group of specially designed spring motors were procured for evaluation purposes. Some of these were retained for transport experiments while others were submitted to several manufacturers for application of a magnetic recording coating. All tapes were 0.002 in. Dynavar, ¼ in. wide and 100 in. long and designed for constant torque over a 32-turn travel on a one inch reel. Results of torque tests made on all springs (Fig. 17) demonstrated that constant torque is maintained within 15% over the entire travel of the motor. The damping device employed to control tape speed during the record mode consisted of a fixed nylon cylinder placed within the magnesium spring motor drive drum. The gap was filled with 200 centistoke, Dow Corning "200" silicon fluid. The damping assembly was designed so that the differential thermal expansion of the two drums compensates for the temperature coefficient of fluid viscosity, thus maintaing a constant torque-speed relationship over a wide temperature range. The performance of the velocity damper is indicated by the curve of Fig. 18. Speed remained essentially constant over the range of 20 to 50°C. Early designs of the damping device depended on capillary attraction for fluid entrapment. Difficulties arose because of the escape of fluid from the damping chamber which caused erratic speed variations due not only to the loss of damping fluid but also to its deposit on the tape. A subsequent redesign alleviated these problems by effecting a seal of the fluid in the damping chamber.

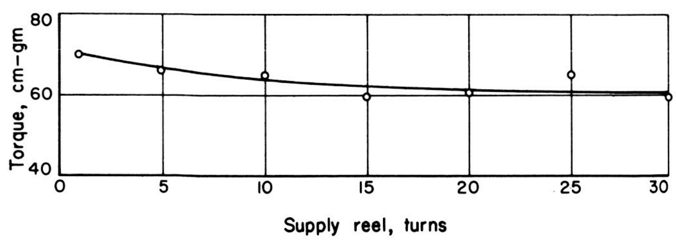


Fig. 17. Torque Curve of Neg'ator Spring Motor

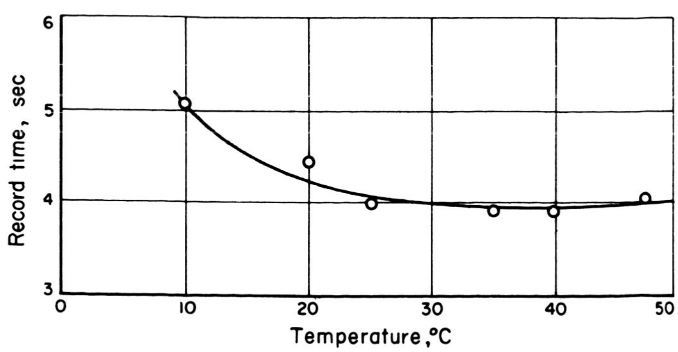


Fig. 18. Speed Curve of Neg'ator Spring Motor

In order to study the switching, timing and mechanical functions, a breadboard model was assembled (see Fig. 19). Timing-function studies on this unit determined the sequence of switching events required for satisfactory performance of the mechanism. The tape-transport elements were assembled in their final form and tests were conducted to ascertain the proper positioning and tensioning of the head, reels, guides, and rollers for smooth tape travel and intimate head contact during the record mode.

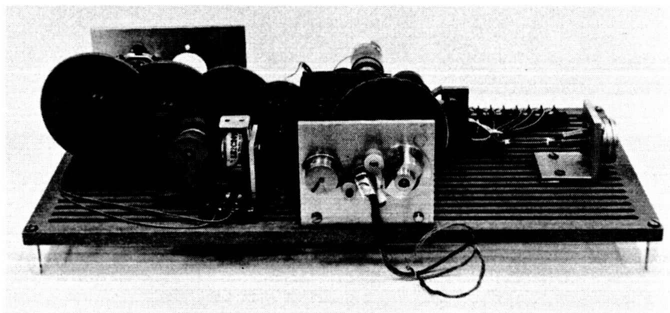


Fig. 19. Breadboard Model of Tape Transport Mechanism

The tape-release latch mechanism, which operates concurrently with shutter actuation, required special design treatment because of the heavy load and limited travel-capability of low power solenoids. Several nonlinear and regenerative latching mechanisms were considered with the eventual selection of a regenerative type with roller follower for use in the initial transport design. Later modifications, to accommodate the change in mission, considerably reduced the latch loading, and a degenerative mechanism with roller follower was used in the final design. A special release solenoid was designed by Luther Mfg. for use in this application. This solenoid was of the movable coil type and was designed to exert a constant force of seventy grams through a distance of .06 in. The solenoid operated on a nominal voltage of 6 volts and required 1.2 watts when producing full rated force. Efficiency was therefore near sixty grams per watt, considerably greater than can be achieved with stationary coil types of comparable size and weight. The air gap between coil-form and Alnico magnet was a nominal 0.007 in. with coil concentricity rigidly maintained for maximum efficiency. Effective coil width was approximately 0.25 in. to minimize flux end effects. The entire assembly was 0.75 in. in diameter, 0.62 in. long and weighed 20 gms.

A miniature, high efficiency, low power motor was specially designed by Luther Mfg. for use as motive power in the playback mode. The initial design goals were realized and are as follows:

1. Output shaft speeds: 2000 rpm
2. Output shaft torque: 0.05 in-oz
3. Input voltage: 7.2 volts
4. No load current: 2 ma
5. Weight: 3 oz
6. Size: 1¼ in. dia x 1¼ in. high

The motor was a D'Arsonval type having an impregnated coil structure and an integrally moulded shaft and commutator assembly. The motor shaft was supported by ball-pivot bearings. An internal gear reduction was included for obtaining the proper output shaft speed. All moving parts were carefully balanced to minimize vibration effects on tape travel. Measured motor efficiencies were in excess of 80% and the no load current requirement of 1.5 ma proved to be less than the design limit specified.

C. *Initial Vidicon System Design*

Figure 20 gives a block diagram presentation of the first complete Vidicon camera system which consisted of the control, record, and playback sub-systems with their associated mechanical components. Basic function of the system was to sense that the Lunar image was in the field of view of the Vidicon camera, record the image at that instant, store the information on magnetic tape, and eventually recover the intelligence by replaying the tape into a voltage controlled oscillator feeding the airborne transmitter.

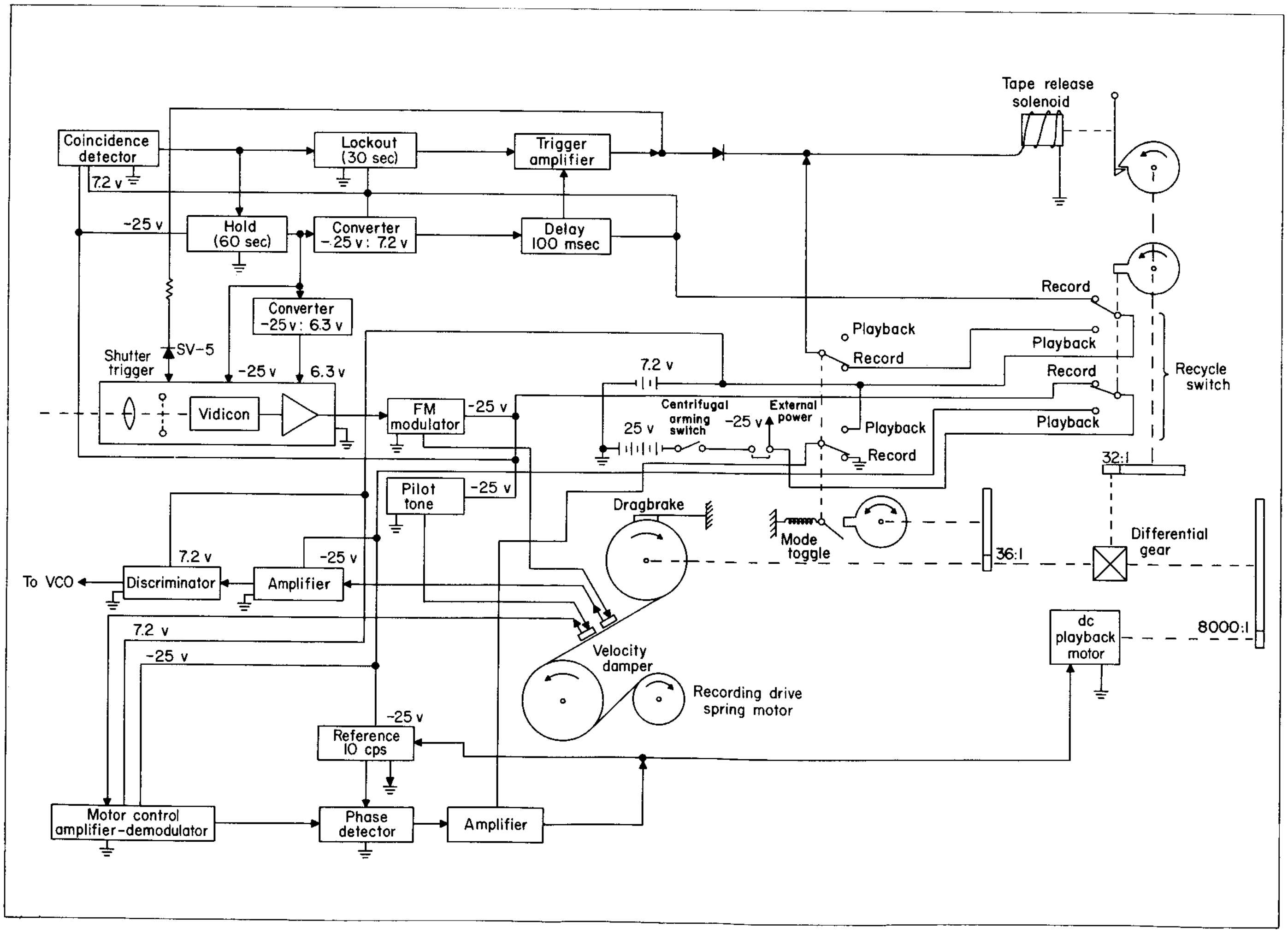


Fig. 20. Complete Camera System

1. ***Sequence of Events.*** The arming switch closes upon completion of the probe de-spinning operation, applying power to the coincidence, control, and record circuitry. The system is now ready to take a picture. As the probe reaches the vicinity of the Moon, the Lunar image eventually energizes both photodiodes in the coincidence detection circuit whereupon a 100-msec pulse is applied to both the 60-sec hold and 30-sec lock-out circuits. The pulse causes the 60-sec hold circuit (basically a one-shot multivibrator) to change state, providing bias and filament power to the Vidicon. The pulse also energizes the 30-sec lock-out circuit, but is prevented from reaching the tape release solenoid and camera shutter by the trigger amplifier gate which is opened 100 msec after the initiating pulse has decayed. Successive pulses are now blocked by the lock-out circuit for a period of 30 sec.

If conditions are normal, the next coincidence pulse will arrive after approximately 10 sec (since the nominal probe spin rate is 6 rpm). This pulse assures that the hold circuit provides power to the Vidicon for an additional 60 sec but is blocked in the lock-out channel. (It should be noted that a single extraneous pulse, such as might be obtained by two stars energizing the two detection diodes, will not cause the system to complete its recording sequence although the Vidicon will draw power from the batteries for 60 sec.) The action of the lock-out circuit permits the Vidicon to warm up for about 30 sec, a mandatory requirement, after which time video information can be obtained.

Thus, a coincidence pulse arriving approximately 30 sec after the initiating pulse, is passed by the lock-out circuit, gate, and trigger amplifier and simultaneously trips the camera shutter and tape-release solenoid. FM modulated video intelligence as well as a 20-kc pilot signal are now supplied to the two magnetic heads and the information is recorded on the tape as it moves past the heads at a constant speed of 20 in./sec driven by the spring motor. As the tape approaches the end of its travel, i.e. about 4 sec after starting, the cam geared to the capstan has completed one revolution and trips the mode toggle switch to the playback position. Thus, power is supplied to the dc playback motor and the tape release solenoid is readied for re-cycling.

One tenth second after the mode toggle is operated another cam geared to the differential sets the re-cycle switch to the playback position, thereby completely disarming the control circuitry and thus disconnecting the Vidicon. Playback speed is 0.010 in./sec and is held constant to better than 0.1% by comparing the recorded pilot signal with a 10-cps reference signal and applying a voltage proportional to the phase difference to the dc playback motor. The FM video signal recorded on the second channel is passed through an amplifier-limiter-discriminator and fed to the voltage controlled oscillator as low frequency video.

At completion of playback, e.g. after approximately two hours, two complete picture frames have been transmitted, and the mode toggle switch is tripped back to its original position. The tape release solenoid is thus energized and again releases the stop cam, allowing the spring motor to transport the tape to the opposite end. The mode cam now trips the toggle, thus disconnecting the solenoid (thereby latching the stop cam) and energizing the playback motor.

The playback cycle above is now repeated until the playback circuitry supply or motor power is exhausted.

2. ***Control Circuitry.*** The control circuitry for the Vidicon camera system consisting of three functionally separate circuits has been briefly described earlier in this Report. (See Fig. 21 for Schematic Diagrams.) All components are mounted on two printed circuit boards which are in turn mounted on both surfaces of the tape deck. (See Figs. 22 and 23.) The final circuitry utilizes transistors exclusively to accomplish the required functions. To eliminate extraneous pulses, produced as a result of interaction between the 60-sec hold and 30-sec lock-out circuits, it was necessary to use different bias supplies for these two circuits. The idling power requirement for the entire control system is under 25 milliwatts and total weight, including circuit boards, is approximately sixty gms.

The 30-sec lock-out circuit utilizes two transistors both of which normally operate in the cut-off mode. The circuit therefore requires very little idling power. An incoming negative pulse momentarily saturates both transistors allowing an initially-uncharged timing capacitor to charge up quickly to the full supply voltage. This, action in turn, cuts off both transistors and allows the capacitor to discharge slowly in exponential fashion. As long as the capacitor voltage exceeds the amplitude of the pulses applied to the circuit, these pulses are blocked. Pulse amplitude and the R-C discharge circuit are adjusted for a lock-out

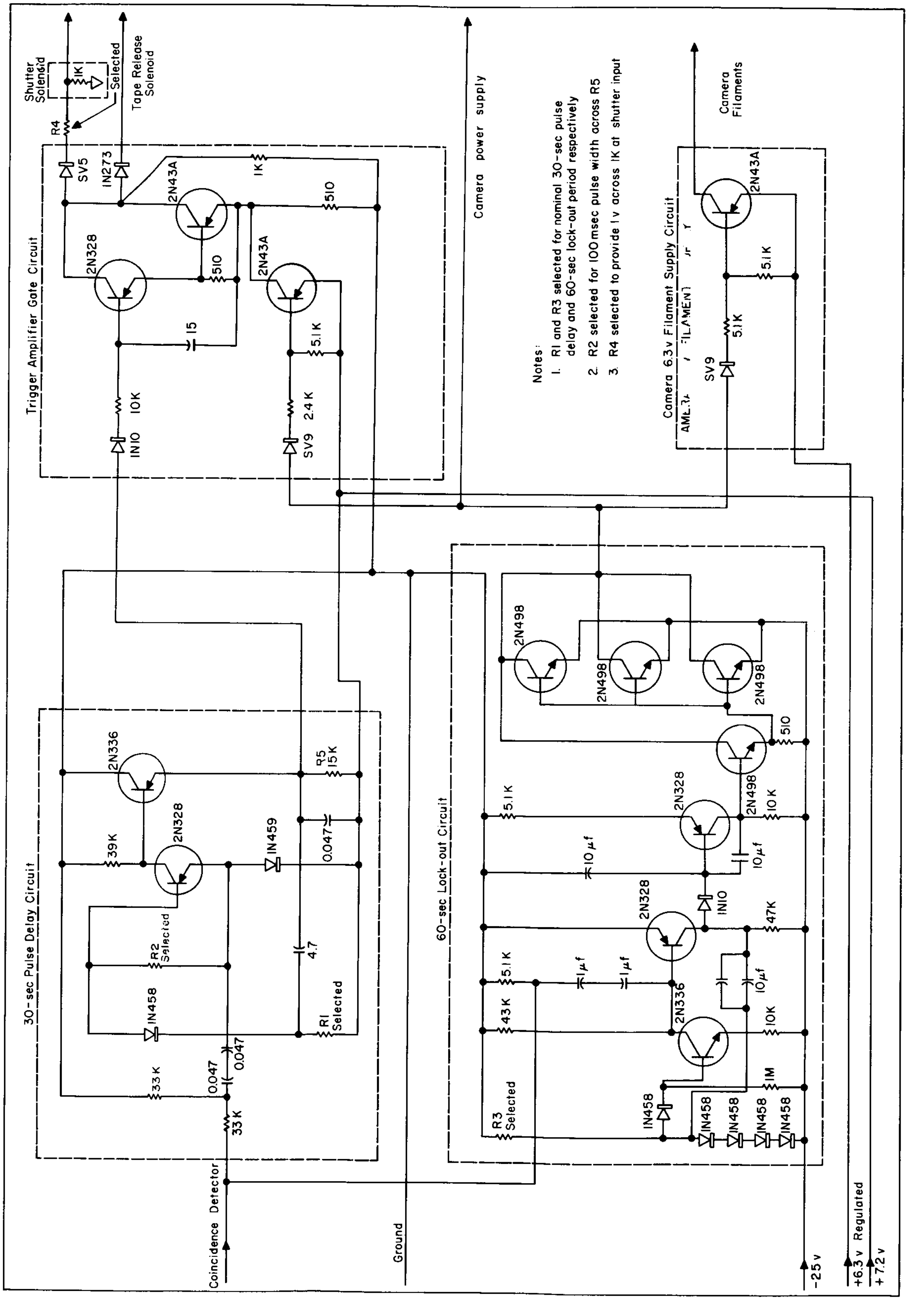


Fig. 21. Camera Control Circuits

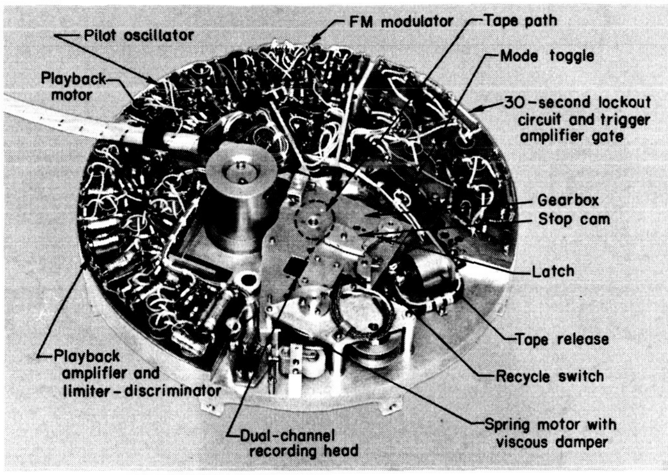


Fig. 22. Tape Recorder, Top

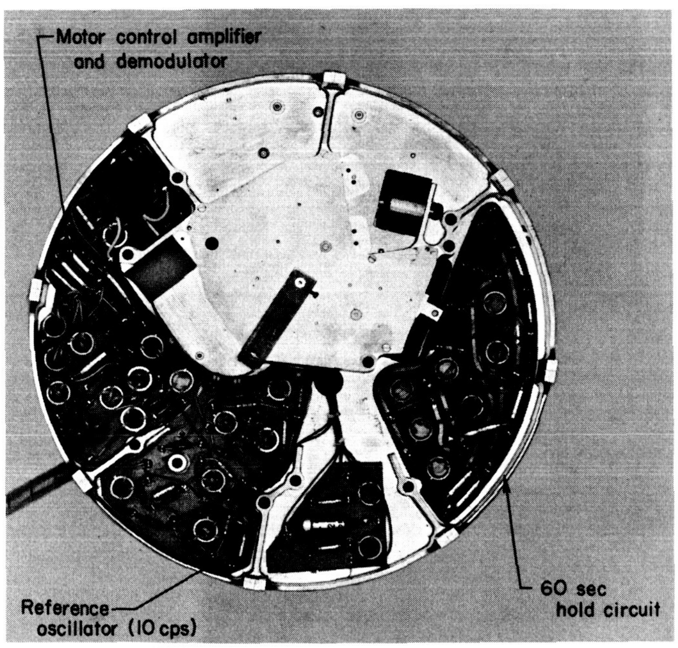


Fig. 23. Tape Recorder, Bottom

period of 30 $\pm$ 2 sec after which time an impressed pulse is allowed to pass to the trigger amplifier by the action described above.

The 60-sec hold circuit employs seven transistors, two of which are normally saturated with the remainder being cut off. Both a negative and a positive pulse (derived from the negative pulse) are applied, in that order, upon optical coincidence. In the normal state, the timing capacitor connected between collector and base, respectively, of the two saturated transistors is fully charged. The first negative coincidence pulse has no effect on the circuit except for driving the two transistors in the input stage slightly more into saturation. The derived positive pulse, arriving approximately 100 msec later, changes the operating mode of both transistors to cut-off. This action, in turn, saturates the remaining five transistors after a time delay of approximately 200 msec, and also causes the timing capacitor to discharge slowly through a high resistance. Saturation of the output transistors thus provides power to the Vidicon about 300 msec after a Lunar coincidence and simultaneously opens the trigger-amplifier gate. A succeeding negative coincidence pulse momentarily saturates the two input transistors and allows the capacitor to charge up quickly to full voltage through a low resistance.

During this period the output stages would be cut off, except for a memory capacitor which has been included to prevent the sudden voltage fluctuation from appearing at the output. The derived positive pulse then reverses the operating modes of the input and output stages, again slowly discharging the timing capacitor. The timing circuit is adjusted such that the output stage remains in conduction for 60 sec after application of the last pulse. After that time, the capacitor voltage having dropped below a required minimum value, the circuit restores itself to the original condition.

Three transistors are utilized for the trigger-amplifier gate circuit. The power output stage feeding the tape-release solenoid is normally cut off. The gate circuit is closed until 300 msec after application of the coincidence pulse at which time power is applied to the emitter of the output transistor from the 60-sec hold circuit. A negative pulse from the 30-sec lock-out circuit will saturate the output stage of the gate for the duration of the applied pulse thus providing the necessary power to operate the solenoid.

3. FM Modulator and Pilot Oscillator. Two types of signals were to be recorded on the magnetic tape: (1) A pilot tone which was to be a fixed-frequency signal of nominally 20kc, and (2) a 20-kc signal, frequency-modulated by the 10-cps to 10-kc video information.

In order to simplify instrumentation and allow for a maximum degree of flexibility, both the FM and pilot channel modulators were made identical. These are shown schematically in Fig. 24. The oscillator is of the two-terminal current controlled type generating spikes of signal energy at a 40-kc rate. These spikes are con-

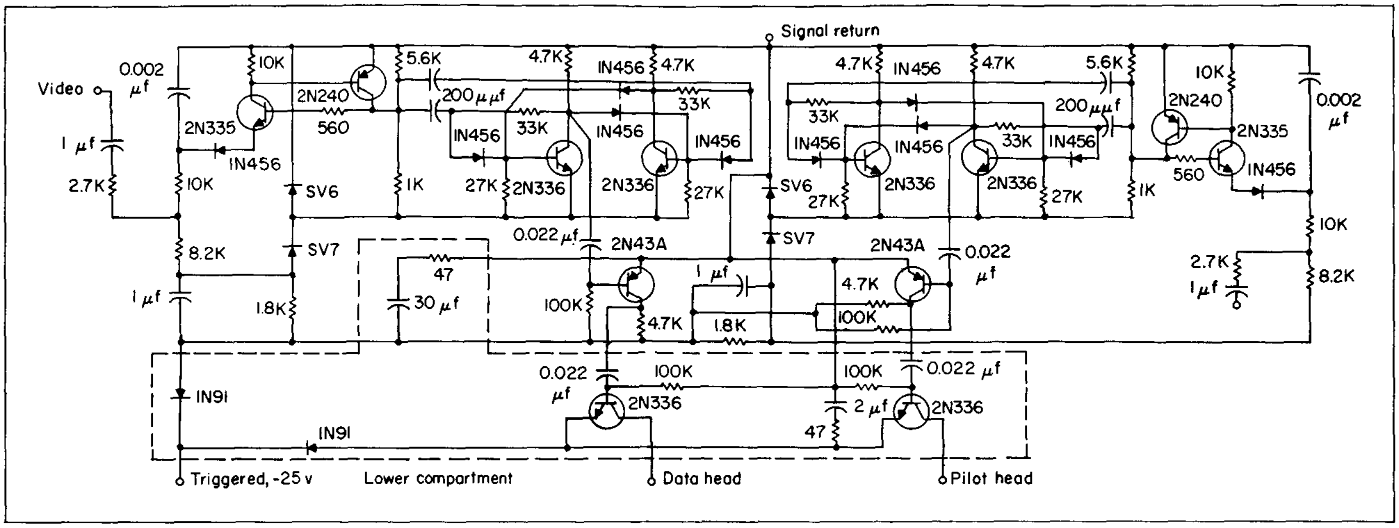


Fig. 24. FM Modulator and Pilot Oscillator

verted to square waves by a binary counter and the resultant signal is amplified to saturation in switching stages activated by the −25 volt power supply. In order to impress saturation-density signals upon the tape it is necessary to feed 20-kc square-wave signals of at least 25 volts peak to the high impedance head. Experimental evidence confirmed the superiority of the square wave over any other waveform, particularly over the wide frequency deviations to be encountered by the head.

Although several germanium transistors are used in this design, there was no significant deterioration of performance at temperatures up to 85° C.

4. Playback Amplifier and Discriminator. Upon playback, the magnetic head yielded a 10-cps carrier at a signal level of the order of −90 dbm. It was necessary to generate square waves from this signal of 7 volts peak with completely negligible rise-time. Under extreme conditions of tape drop-out and slow rate, the input signal could drop to levels of −120 dbm and possibly rise to levels of −85 dbm. For these signal amplitude variations, it was necessary to design the circuit so that the limiter square-wave signals would suffer a minimum duty-factor variation. The signal was then to be discriminated and any vestigial carrier completely removed.

The video playback schematic is shown in Fig. 25. This consists of (1) a nine-stage 160-db gain amplifier designed to accept a bandwidth of 5 cps to 20 cps, (2) a video discriminator, and (3) a two-stage low-pass active filter with a 4-cps cutoff and 24 db/octave rolloff. The discrimination process referred to, makes use of the fact that if a capacitor is connected across a nonlinear switch (see Fig. 26) then the nature of E_{out} will be as shown. This can be seen to be identical in nature to a

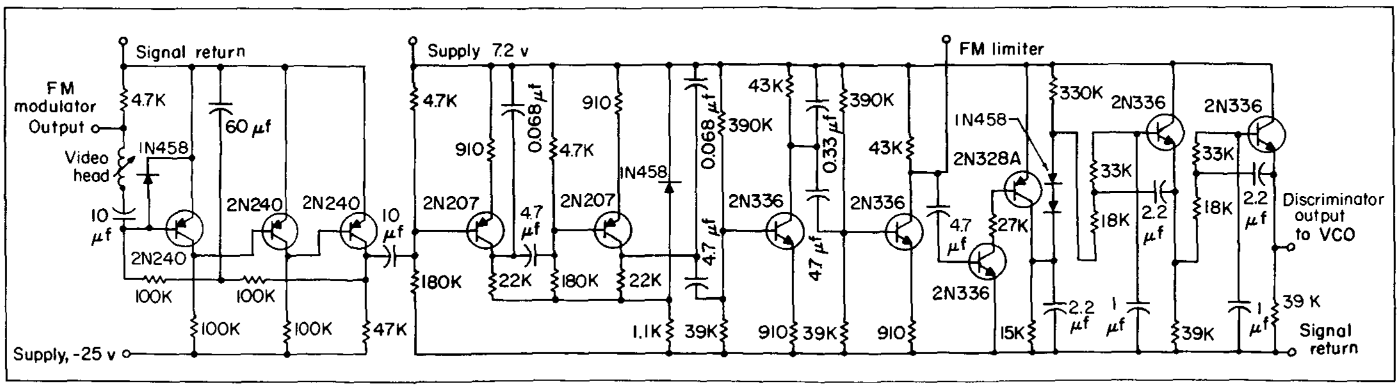


Fig. 25. Playback Amplifier, Discriminator, and Filter

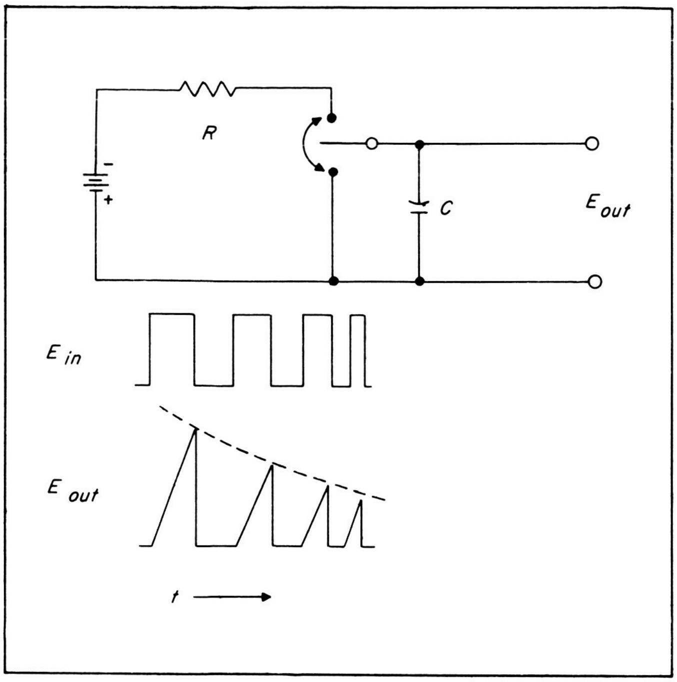


Fig. 26. Discriminator Equivalent Diagram

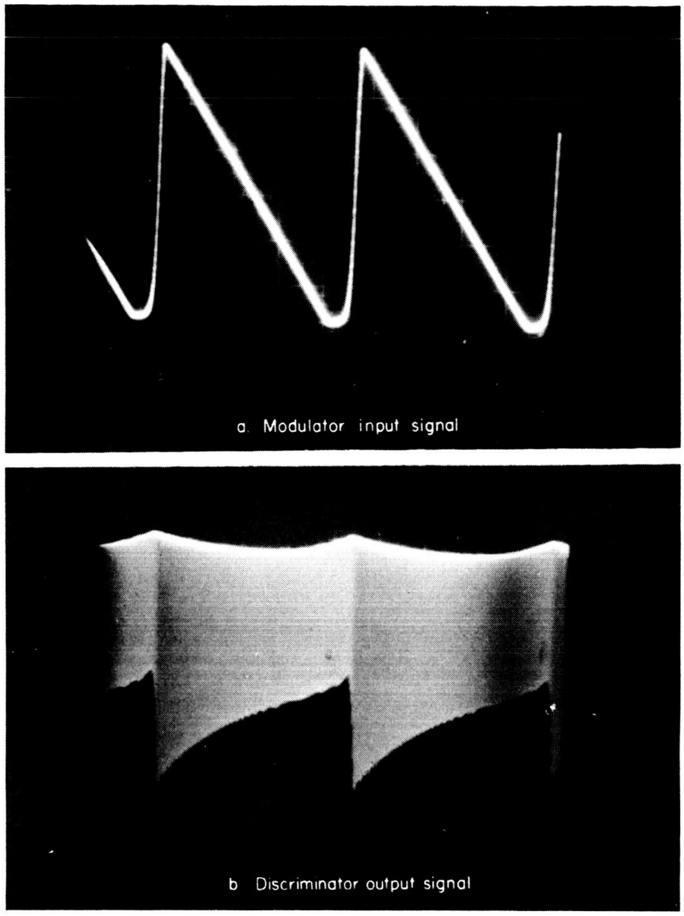


Fig. 27. Discrimination of FM Modulator

half-wave-rectified amplitude modulated carrier. In other words, the FM signal is converted into an equivalent AM signal after the limiting process. It is then necessary only to remove the carrier frequency. This property was utilized during the test phases of the FM modulators, as can be observed from the schematic, since a capacitance of 0.1 μfd across the tape head will convert the FM signal to an equivalent AM signal which is then easily displayed on an oscilloscope. This property is demonstrated in Fig. 27 for a saw tooth modulating pattern. Observe that this signal corresponds to the reciprocal of the modulating frequency.

5. *Motor Control System.* The function of the motor control system is to maintain a constant video-information rate during the playback mode. The system makes use of the pilot signal placed on the tape during the recording process and controls motor speed to maintain phase lock between this signal and that of the 10-cps reference oscillator. In this way precise time indexing of video information is accomplished even though recording speed variations of $\pm$ 20% are observed. The system is shown in Fig. 28 and consists of a high-gain amplifier which has a 7 μv input threshold, followed by a low level feedback limiter and saturated amplifier.

The pilot signal is then demodulated with respect to the reference-oscillator output in a transformerless transistor phase detector, amplified and applied to the drive motor. Loop stabilization is achieved by frequency modulating the reference oscillator with the motor voltage (phase error signal) through a lead network to constrain the oscillator to phase correspondence with the tape-derived signal. The phase and phase rate errors are thereby maintained near null.

The reference oscillator used for this purpose is similar in operation to the FM and pilot oscillators described in Part C-3 with some additional consideration given to long term frequency stability with respect to voltage and temperature variations. Tests made on the circuit demonstrated timing stabilities of 0.1% over long intervals where deviation demands were held below 60% of the base frequency. Tests of the complete control system indicated a locking range in excess of $\pm$ 50% of the base frequency with stable operation beyond these limits

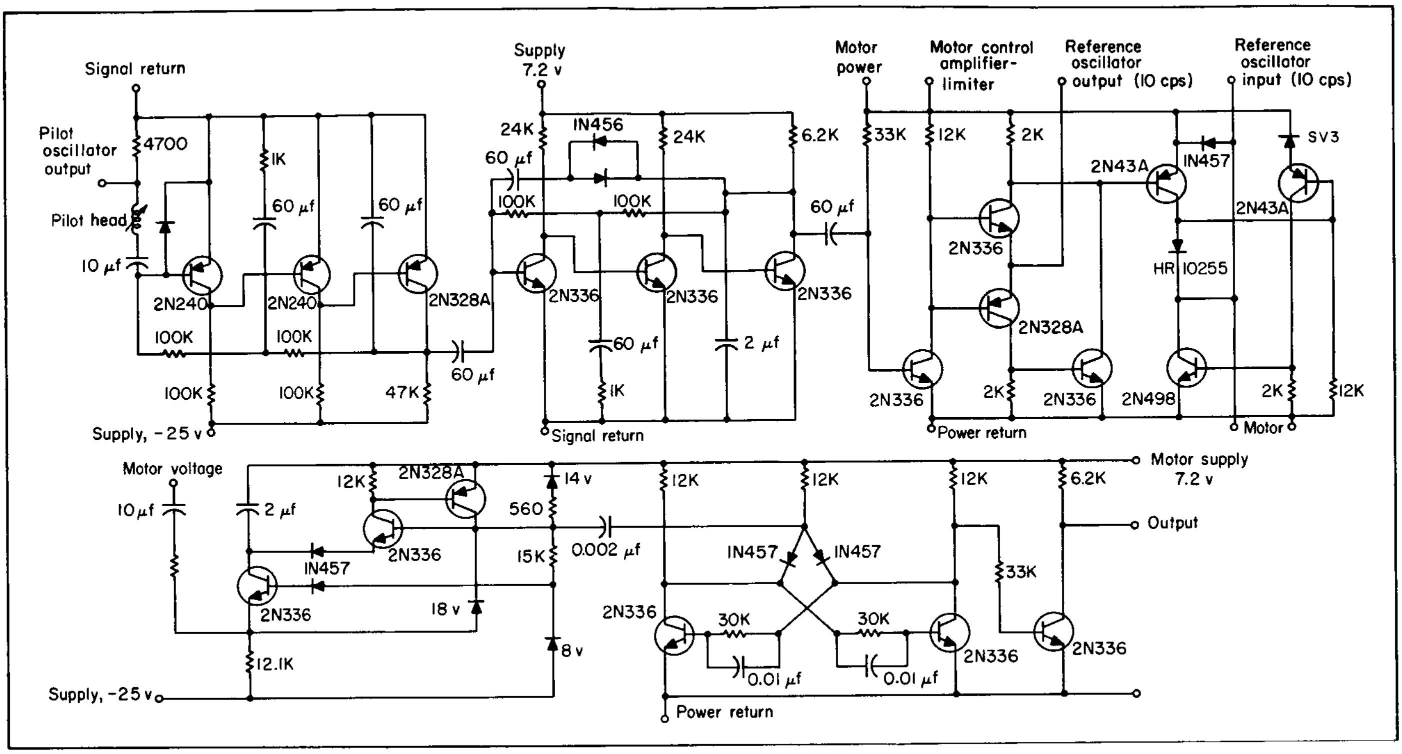


Fig. 28. Motor Control System

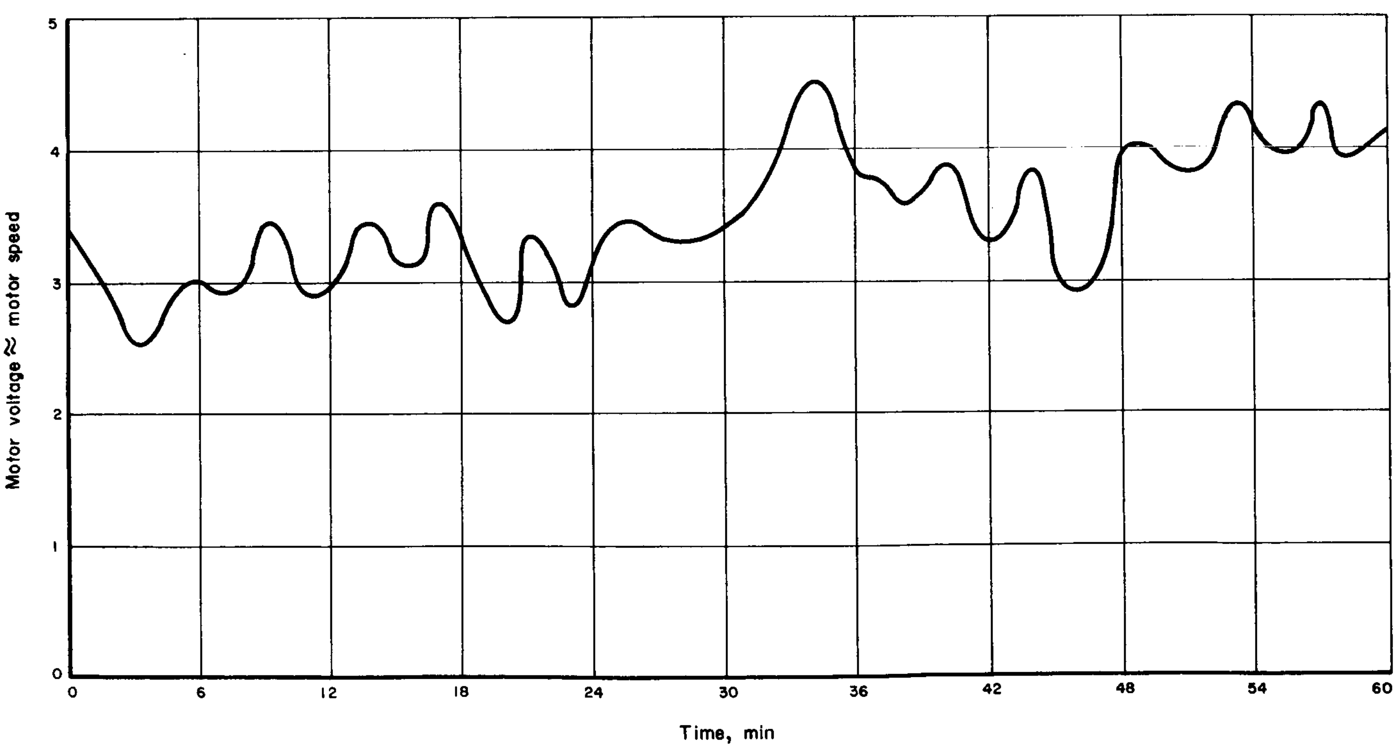


Fig. 29. Motor Control System Performance

IV. PERFORMANCE EVALUATION OF THE INITIAL SYSTEM

under low noise conditions. Figure 29 is a reduced data sample of motor voltage variations of an actual video playback over a two hour period. Motor lock was maintained during the entire period. These data contain indications of recording tape speed variations caused by random frictions, flutter, capstan eccentricities and drive gear irregularities.

Full scale system tests began in mid-December, 1958. Prior to this time the transport mechanism and individual circuit modules had been completed and functionally tested. Compatibility checks of the control circuitry and switching functions were made first and proved satisfactory. Tests were then directed to the recording circuitry and a video recording attempt was made. Playback of this tape revealed that the recorded signals were well below the expected levels, and in fact, were nonexistent on the pilot channel. An examination of the data channel showed severe amplitude variations including a periodic suppressed-carrier modulation pattern characteristic of tape flutter conditions. A series of tests were made which resulted in the partial correction of both conditions through reorientation of the head position in two planes. Vertical misalignment of the head caused the tape to ride on an end ridge, and unequal tensioning of the tape over the entire pole face structure were determined to be the causes of the pilot-channel signal loss. Increased wrap-around was found to improve but not eliminate the flutter condition. A new attempt at playback revealed the presence of extreme noise impressed on the recovered video signal. Close examination of the transport mechanism showed that tape speed irregularities existed which were traced to the combination effect of head-to-tape and drag-brake stiction on gear-train compliance. Before and after photographs of a marginally successful video signal recovery are shown in Figs. 30 and 31.

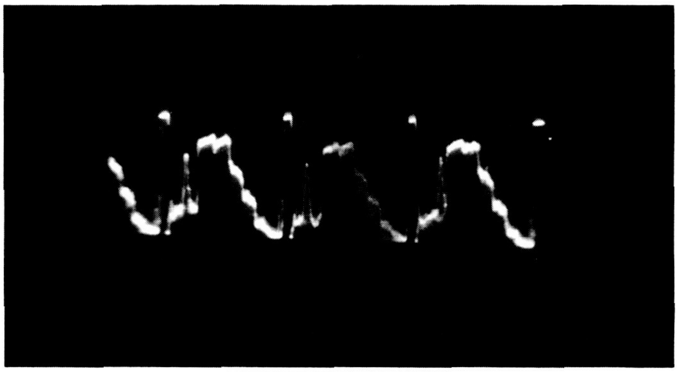


Fig. 30. Video Camera Output Signal

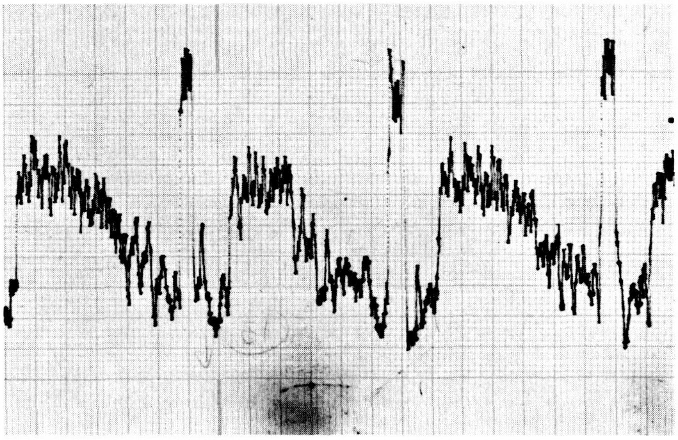


Fig. 31. Video Output of Tape Recorder

V. SUPPLEMENTARY DEVELOPMENT OF THE VIDICON SYSTEM

From the results obtained in testing the first vidicon system it was evident that additional development work would have to be undertaken if the original design objectives were to be achieved. In particular, since low speed video noise apparently constituted the most serious problem, it was decided to concentrate re-design efforts in such areas of the system as were suspected to be the main sources of this noise. Thus, further investigations on the tape transport mechanism, magnetic head, and electronic record-playback circuitry were started. Concurrent with these efforts a program leading to development of improved ground recovery equipment was undertaken.

A. Tape Transport Mechanism

The flight-model tape transport mechanism was suspected of contributing to video noise in four ways:

1. Gear tooth modulation
2. Ball bearing noise
3. Tape slippage due to being reel driven
4. Unshielded head

In order to further investigate the video noise problem, a breadboard tape transport system with a 2000:1 record-playback speed ratio was constructed. (See Fig. 32.) This mechanism attempted to minimize noise contribution by having the following features:

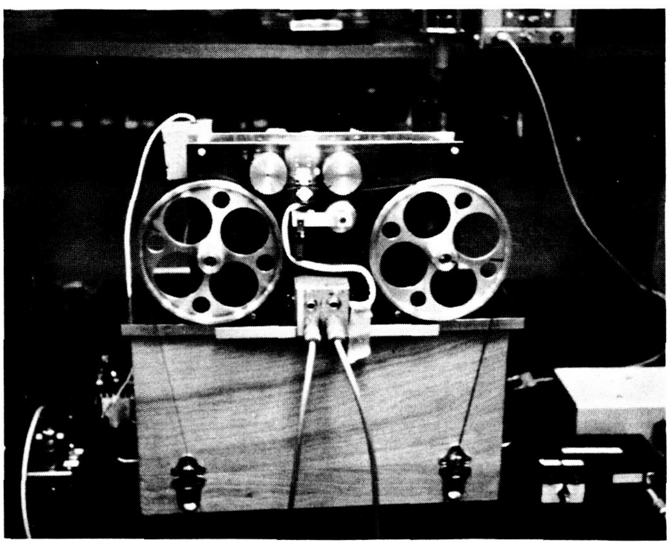


Fig. 32. Gearless Tape-Transport System Breadboard

1. Gearless speed reduction from motor to capstan (The speed reduction was made up of three stages of puck and pressure roller drive.)
2. Journal bearings throughout
3. Capstan driven tape with a pressure roller system
4. Constant tape tension throughout tape length
5. A magnetically shielded head

The breadboard system contributed significantly toward establishing design criteria that would be useful in the redesign of the flight model. Its contribution to system noise level was reduced to less than 1%. Although the noise contribution from the gears and ball bearings was not positively identified, it is probable that a system without gears or ball bearings is preferable. The tape should be capstan driven and constant tension should be maintained on it throughout its length of travel. Time limitation on the project did not allow redesign and construction of a new flight model mechanism based on these findings.

1. Recording Subsystem. While fabrication of the laboratory-breadboard tape deck was in progress additional tests were undertaken to determine the effects of packing density and recording current levels. Tests were also made on instrumentation type tape, high output tape and a special metal coated tape processed by Packard Bell Corporation. Purchase orders were initiated for combination record-playback heads which were to be designed specifically for high output at slow tape speeds in the playback mode.

Results of the tape tests revealed that the Packard Bell tape had approximately the same output as the instrumentation tape and 15 to 50% (depending on packing density) less output than the high output tape. The Packard Bell tape required twice the recording current of the high output tape for maximum output. (See Fig. 33.)

Accepting the high output tape as the one best suited to the requirements, further tests were performed on this tape. These tests were made at varying tape speeds, packing densities, recording frequencies, and recording currents. The results indicated that it was not feasible to expect a consistently useful output from the playback head when playing back packing densities of 1000 cyc/in. at tape speeds of 0.01 in./sec. (See Figs. 34 and 35.)

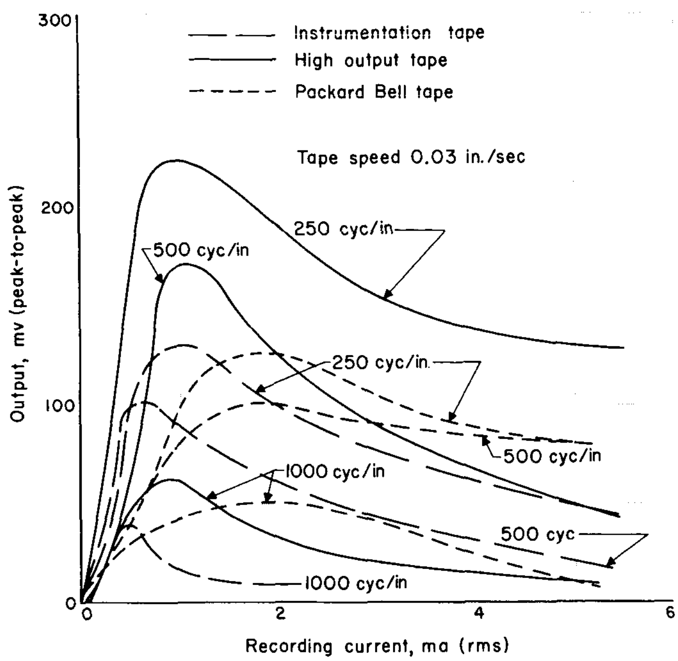


Fig. 33. Tape Output Voltage vs Recording Current

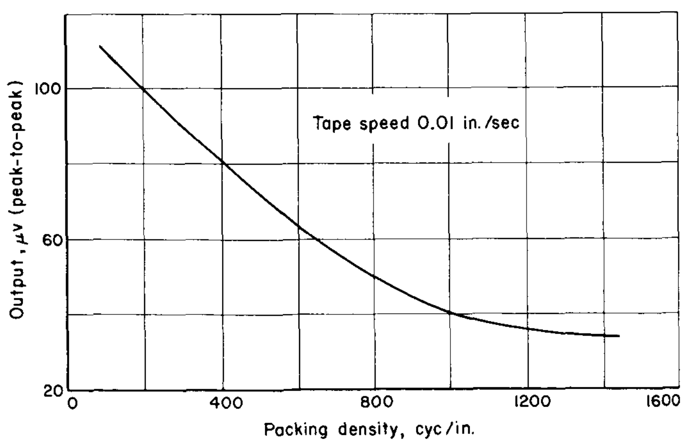


Fig. 34. Tape Output Voltage vs Packing Density at Constant Recording Current of 0.5 ma rms

Upon completion of the laboratory-breadboard tape deck, additional tests were made, using the high output tape, to spot-check earlier data.

Figure 36 gives a comparison of typical outputs at different packing densities. The extremely low output obtained from tapes packed at 1000 cyc/in. and played back at 0.01 in./sec made it desirable to decrease the packing density which had been used previously. Since a marginal output could be obtained from a 670-cyc/in. packing and a more than adequate signal from 330-cyc/in. packing, it was decided that future system tests would be made using 500 cyc/in. as the nominal packing density for all video recording. This change was accomplished by doubling the capstan diameter, thereby doubling the tape speed both in the record and playback mode.

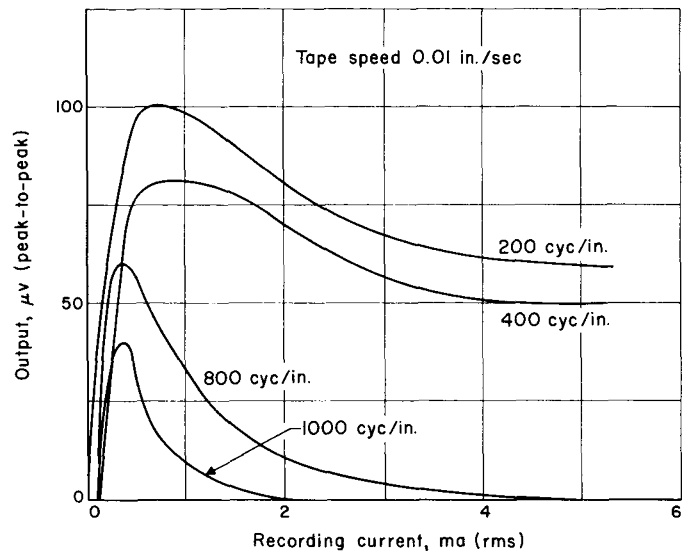


Fig. 35. Tape Output Voltage vs Recording Current

A problem which developed when recording at lower packing densities was the inability to record information over a previously recorded tape. At packing densities of 500 cyc/in. and lower, severe distortion occurred when playing back a multiple recording. This problem did not manifest itself at the higher packing densities.

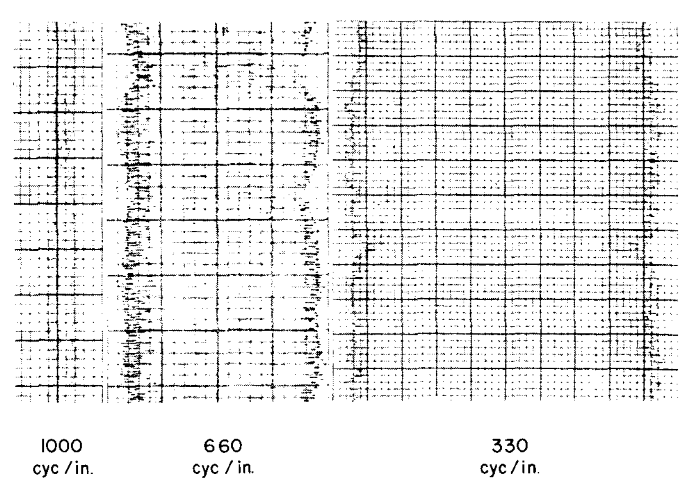


Fig. 36. Typical Relative Outputs for Different Packing Densities

Figure 37 is a typical signal from the playback head after being amplified by a factor of 5 x 10^4. The recorded signal was an 18 kc sine wave recorded at 0.5 ma and 38.7 in./sec. Playback frequency was 11 cps.

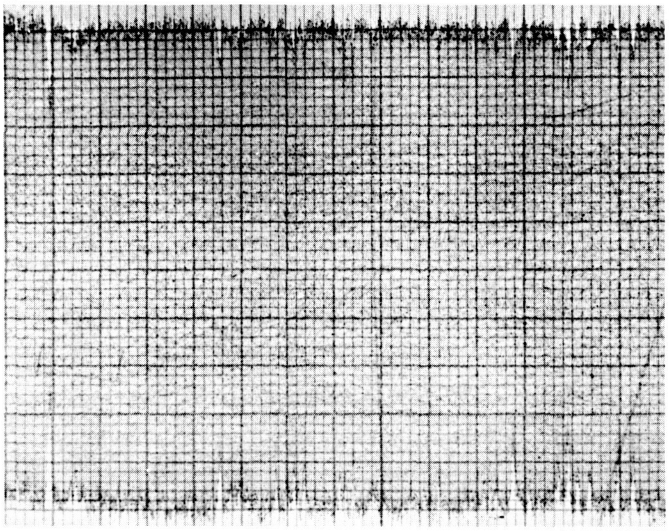


Fig. 37. Recording of 18-kc Sine Wave Showing Amplitude Variations on Slow Speed Recovery

Figure 38 represents the amplified playback-head output for a 19-kc carrier, frequency modulated by a 100-cps square wave. Note the variation in output-signal amplitude with varying packing density which is caused by the modulation process.

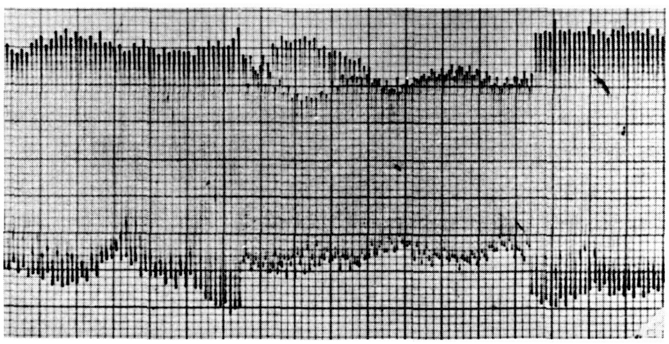


Fig. 38. Slow Speed Recording of 19-kc Sine Wave Modulated by 100 cps Square Waves

Figure 39 shows the amplified playback-head output for a 19-kc carrier modulated by a simulated video signal after being amplified by a factor of 5 x $10.^4$ The "five shades of grey" pattern used is shown in Fig. 49.

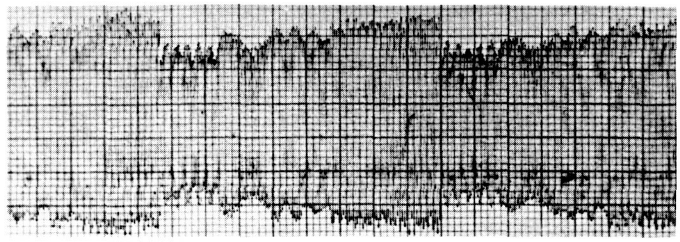


Fig. 39. Slow Speed Recording of 19-kc Sine Wave Modulated by Video Signal

Using the Dyna-Mu head initially selected, it was found that video information could be successfully reproduced when playing back at ultra-slow tape speeds as long as the intelligence was not limited by excessive packing density.

It is believed that, with an optimum-design record-playback head, it would be possible to obtain video information at packing densities much higher than the 500 cyc/in. used so far.

Due to the long lead time for the special heads on order, it has not been possible to confirm this belief by laboratory tests.

B. Electronic Playback Circuitry

The playback circuitry was thought to contribute to low frequency video noise in two ways: (1) noise at the amplifier input and (2) noise generated by the FM detector.

To minimize the former, the input circuitry was carefully shielded during all ensuing tests, and it was then assumed that the remainder of the noise was generated in the detector.

Both amplitude variations of the carrier and second harmonic distortion were considered to be largely responsible for the residual detector noise, and consequently a survey of different FM detection methods was made with the aim of selecting a technique that would be less sensitive to these disturbances. As a result, two pulse-counting FM detection circuits were built and their signal-to-noise ratios compared with the detection circuit shown in Fig. 25. The first of these is of the one-shot multivibrator type whose schematic diagram (in the full-wave version) is shown in Fig. 40. Here pulses are applied to the two multivibrators at the time of positive and negative zero crossing of the limiter output signal. On-time in either channel is adjusted to

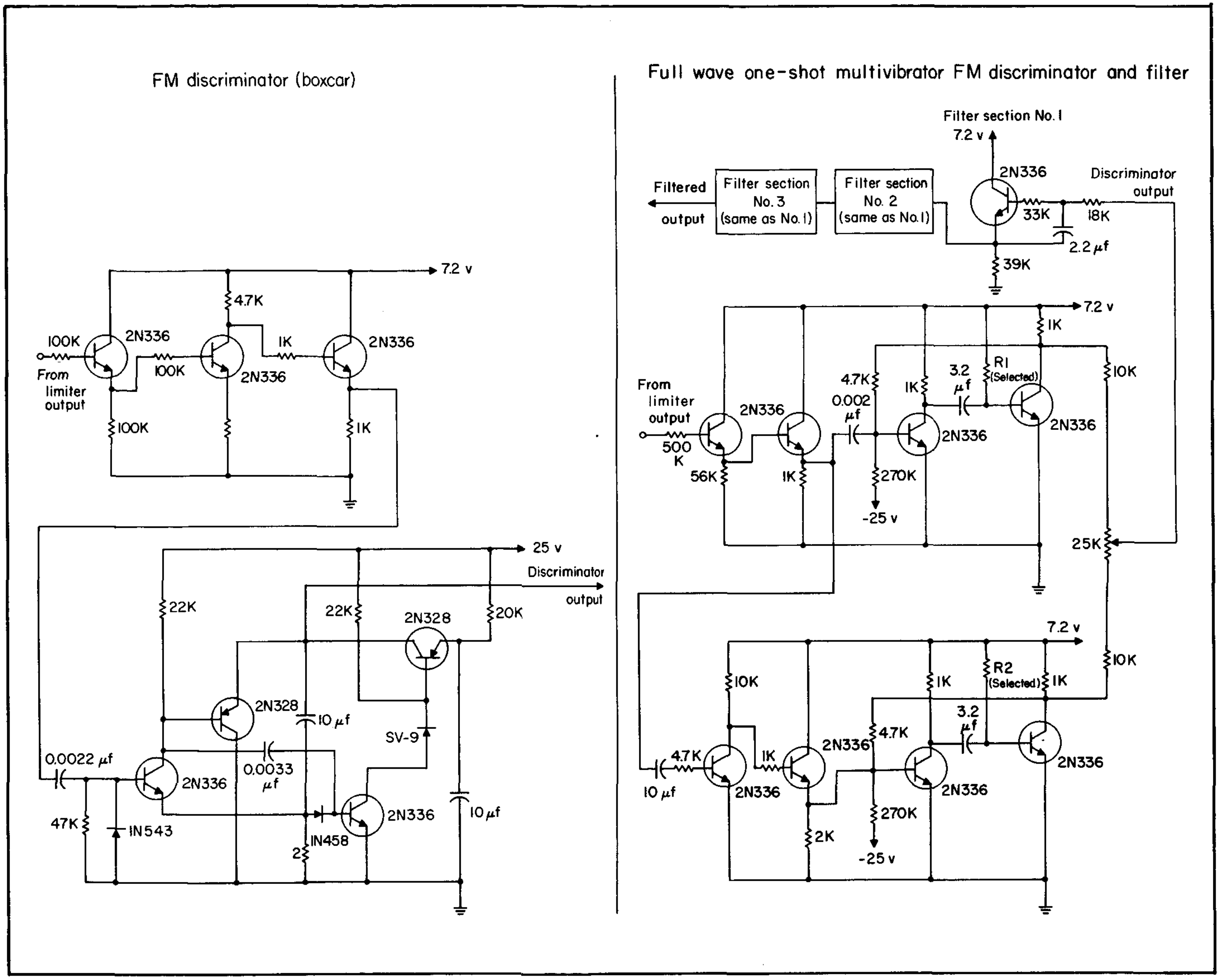
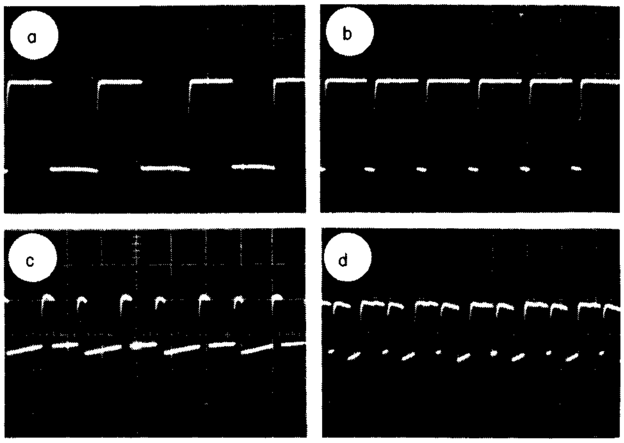


Fig. 40. Boxcar and One-Shot-Multivibrator FM Discriminators

give maximum dc output at the highest expected carrier frequency (approximately 14 cps) and wave shape symmetry at the low frequency end (about 8 cps). The signals are then summed, 1:1, and appropriately filtered. Individual and summed wave shapes at 8 and 14 cps are shown in Fig. 41. For purposes of direct comparison, a constant-frequency sine wave was applied to the playback amplifier which was connected to the two discriminators in parallel. The effect of amplitude variation of the impressed signal on detector operation is presented in Fig. 42. Note the significant improvement in signal-to-noise ratio of the one-shot over the integrating type discriminator and the lack of permanent dc level changes due to signal amplitude variations.

playback attempt, both the modified tape transport mechanism and the previously-developed recording circuitry were used to record a 100-cps square wave. The recovered slow-speed discriminator outputs are shown in Fig. 43. The superiority of the one-shot discriminator with respect to linearity, signal-to-noise ratio, and constancy of dc level is readily apparent. Frequency response is approximately 2 cps for both discriminators. A representation of a slow speed simulated video signal is shown in Fig. 44.

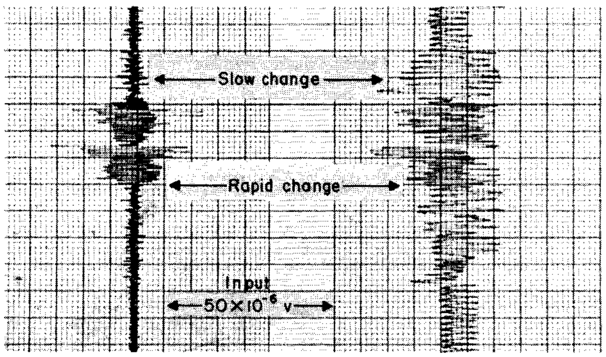
In addition to the work on the one-shot discriminator which has been described, another discriminator circuit of the so-called boxcar type was developed. Theoretically this kind of discriminator does not require elimination



	Scale, v/cm	Limiter frequency, cps
a	1	8
b	1	14
c	2	8
d	2	14

Note: Sweep time = 50 msec/cm

Fig. 41. Output of One-Shot-Multivibrator Discriminator



a. One-shot discriminator — b. Integrating-type discriminator

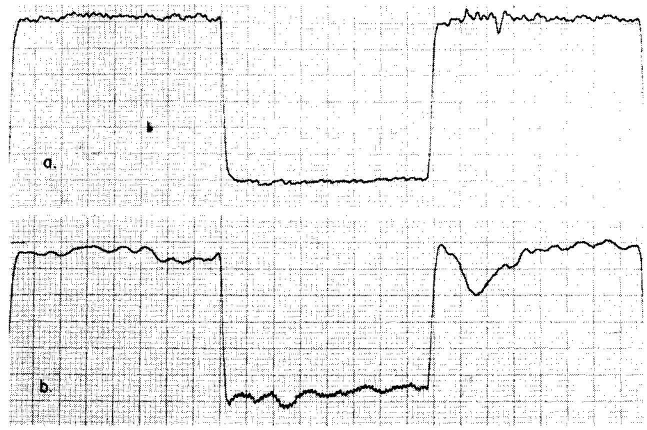
Discriminator sensitivity:	a. 250 mv/cyc	b. 125 mv/cyc
Total voltage swing:	a. 1.5 v	b. 750 mv
Peak-to-peak noise:	a. approximately 6%	b. approximately 15 %

Tape speed: 2.5 mm/sec — Signal frequency: 10 cps

Scale sensitivity: 50 mv/cm

Input signal: varied between 50×10^{-6} and 100×10^{-6} v

Fig. 42. Comparison of One-Shot and Integrating Discriminators



a. One-shot discriminator — b. Integrating-type discriminator

Scale sensitivity:	a. 500 mv/cm	b. 250 mv/cm
Discriminator sensitivity:	a. 250 mv/cyc	b. 125 mv/cyc
Total voltage swing:	a. 1.5 v	b. 625 mv
Peak-to-peak noise:	a. approximately 10%	b. approximately 30%

Modulating signal frequency: 100 cps

Tape packing density: 500 cyc/in. — Carrier frequency: 18 kc

Sanborn recorder speed: 5 mm/sec — Recording current: 0.5 ma (rms)

Applied square-wave amplitude: 4 v peak-to-peak

Fig. 43. Discriminator Response to 100 cps Square-Wave Modulating Signal

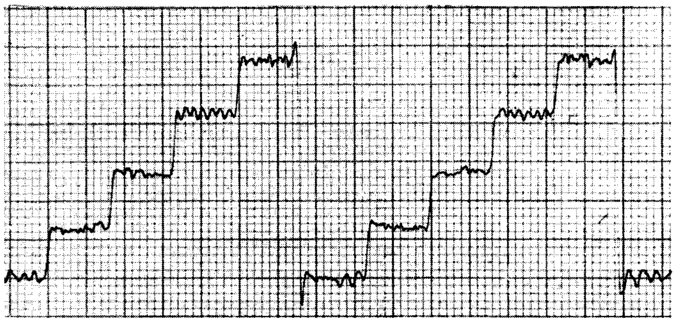


Fig. 44. One-Shot Discriminator Response to "Five Shades of Grey" Simulated Video Signal

of the carrier which results in improved frequency response with fewer components. A half-wave version of this circuit is shown schematically in Fig. 40. Operation is as follows: All four transistors are normally cut off with no charge, or only a small residual charge, on the output capacitor. A positive pulse (derived from the positive-going limiter signal) saturates T-1 for the duration of the pulse, thus reducing the T-1 collector potential. As soon as the pulse disappears, the collector potential tends to rise to the full supply voltage thereby turning on T-3 whose base is capacitively coupled to the T-1 collector. This action, in turn, triggers T-4 into conduction so that a rapid equalization of charge between C_1 (previously charged up to the full supply voltage) and C_2 takes place. Thus the voltage across C_2 rises to one-half the initial value of the potential across C_1 and, provided the impedance seen by the output capacitor is high, will remain at that value until a succeeding positive pulse triggers T-1 and T-2 into conduction, thus resetting the C_2 capacitor voltage to zero. The sequence of events then repeats itself. It should be noted that the R_1-C_1 time constant must be adjusted so that the output voltage is unambiguously related to the pulse frequency. This means that the highest expected pulse frequency must charge C_1 to at least the Zener-diode voltage, with the lowest frequency producing a voltage rise across C_1 just short of the supply voltage. The discriminator output will be very nearly linearly related to the period of the limiter output voltage over the entire range if some sensitivity can be sacrificed at the high frequency end. This is in contrast to the one-shot type discriminator whose output is proportional to limiter signal frequency. It is obvious that the useful frequency range can be extended considerably by appropriate changes of the R_1-C_1 time constant, feedback and output capacitors. Although time did not permit a complete evaluation of this discriminator in relation to the vidicon system, encouraging results were obtained by applying simple waveforms to a voltage controlled oscillator and then feeding the resulting signal into the discriminator. Figure 45 shows the demodulated outputs for a sine, triangular, and square wave input.

C. Ground Recovery Equipment

Initial picture-recovery attempts were based on the use of hard-sync techniques utilizing a sync separator and gated sawtooth generator for both horizontal and vertical sweeps. A block diagram of the complete system including airborne and ground components appears in Fig. 46 which shows the two information-rate conversions required for complete picture restoration. In operation, low rate information is recorded on the ground recorder at 0.02 in./sec and played back into the picture recovery electronics at 30 in./sec yielding a video bandwidth of approximately 3 kc. Sync separation and video dc restoration is accomplished by a peak clamping arrangement which supplies gating pulses to the horizontal sweep generator and restored signal to the ac video amplifier.

The most successful picture recoveries achieved by this method were totally unsatisfactory (see Fig. 47). Subsequent investigations revealed that sync disturbances caused by wow and flutter of the ground tape recorder were the chief offenders. A critical look at all common synchronizing techniques was taken, with the conclusion that each required a high degree of scan-rate periodicity for precise element indexing. Scan rate disturbances of a fraction of a percent produced significant picture distortion. Tests performed on the modified-Ampex ground recorder with slow speed record and high speed playback indicated a wow and flutter content in excess of 5%.

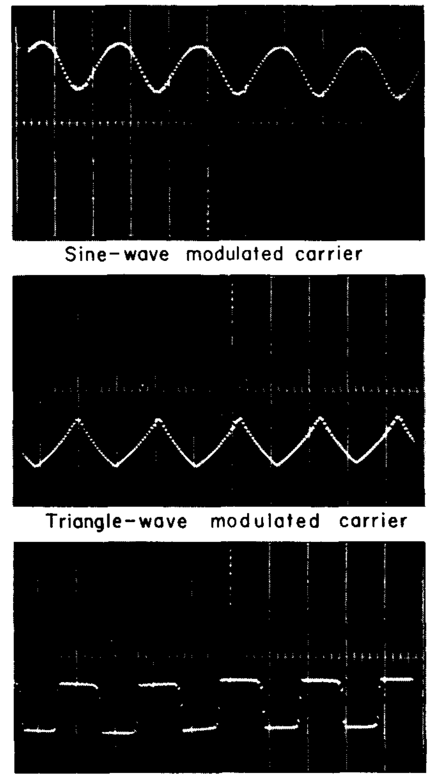


Fig. 45. Boxcar Discriminator Respone to Various Modulating Signals

To eliminate these defects, a less common synchronizing system was breadboarded. Its operation was based on the use of the transmitted pilot tone to index the video information. A block diagram of this scheme is shown in Fig. 48. In this system the vidicon horizontal-sweep signal is derived from the airborne tape-recorder pilot tone through a frequency divider or counter (in this case divided by 180) which supplies reset pulses to the horizontal rate generator. The pilot tone is carried through the airborne tape recorder as the motor-lock signal and transmitted over a very-low-bandwidth telemetry subcarrier. Bandwidth and subcarrier-power requirements

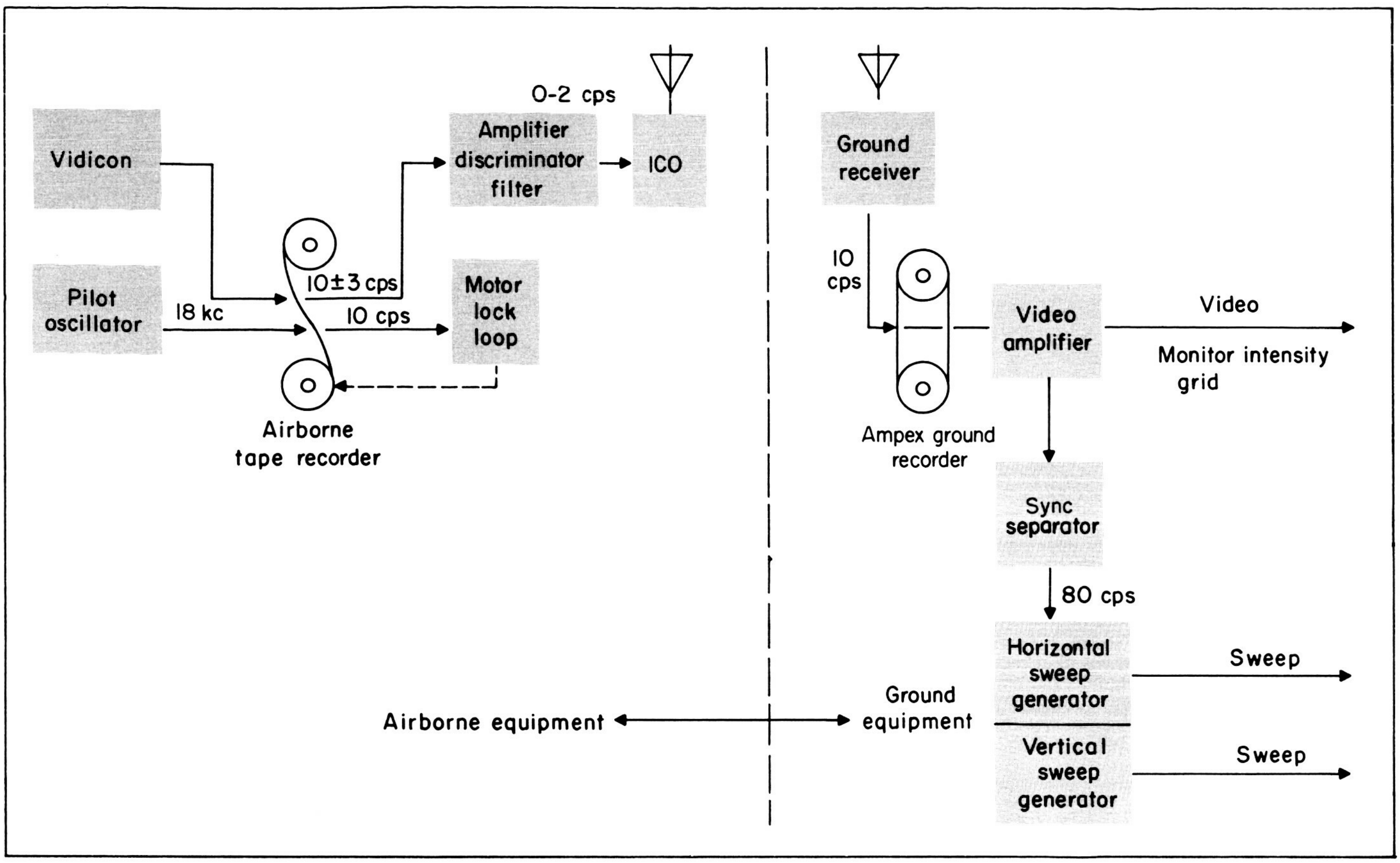


Fig. 46. Airborne Recording and Ground Recovery Systems

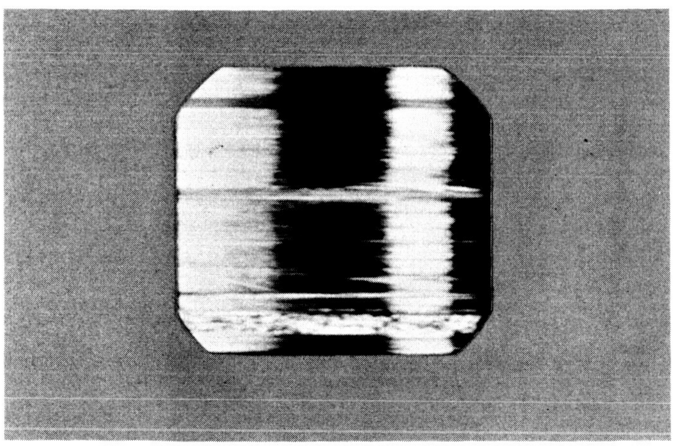


Fig. 47. Unsatisfactory Picture Recovery Using "Five Shades of Grey" Chart

are determined by the frequency stability of the motor-lock oscillator.

At the ground-receiver output the video channel is passed through a discriminator, remodulated to a wide deviation FM signal and recorded on one track of the ground recorder. The pilot signal is also discriminated, but is applied directly to the second track of the ground recorder without remodulation. At the output of the tape recorder, the video channel is discriminated, amplified, and applied to the intensity grid of the monitor kinescope. The pilot channel is fed to a frequency divider whose ratio is identical to that of the flight unit and the resulting pulse resets the monitor horizontal-sweep generator. The pilot channel is also discriminated to provide the rate signal for the horizontal sweep generator. By this technique, the horizontal scan rate varies as the product of all system frequency disturbances and accurately indexes the video information.

A photograph of a ground readout obtained from this system using a free running vertical sweep is shown in Fig. 49. The grey-scale pattern used is similar to that employed in the hard-sync test of Fig. 47. Two aberrations appear in the readout shown in Fig 49. The first is the step jump of synchronism in the lower portion of

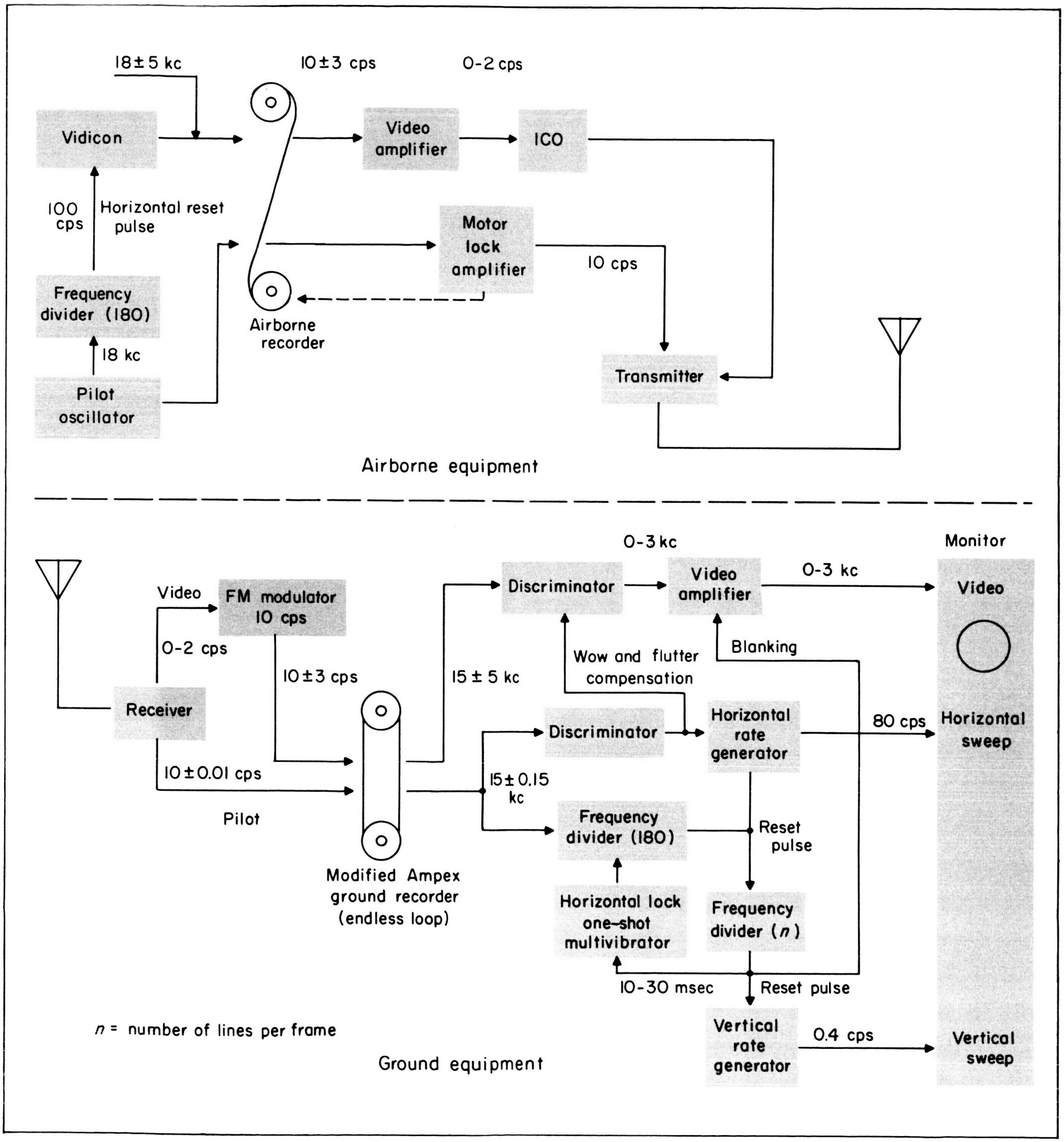


Fig. 48. Modified Block Diagram of Airborne and Ground Systems

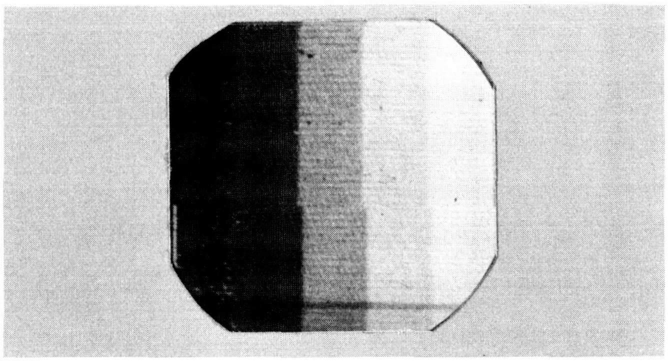


Fig. 49. Grey Scale Sync Pattern

the frame for which no suitable explanation exists. The second concerns the noise observed in the lower portion of the black band which is caused by the low signal level available for that high frequency band. The photograph was taken after approximately 10,000 replays and partial tape erasure may have been caused by inadequate demagnetization of the recording head. Early replays did not exhibit this effect.

Figures 50, 44, and 51 show waveforms throughout the system observed during the test. The simulated video signal applied to the airborne tape recorder is displayed in Fig. 50. The output of the flight unit at slow speed is shown in Fig. 44 and the ground tape recorder output is as seen in Fig. 51. A comparison of Fig. 51 with Fig. 44 shows that approximately 15% peak-to-peak noise has been added to the original signal by the complete system. It is felt that cleanup of equipment and refinement of technique can reduce this figure to below 5% thus assuring an end picture of 10 gray-level quality.

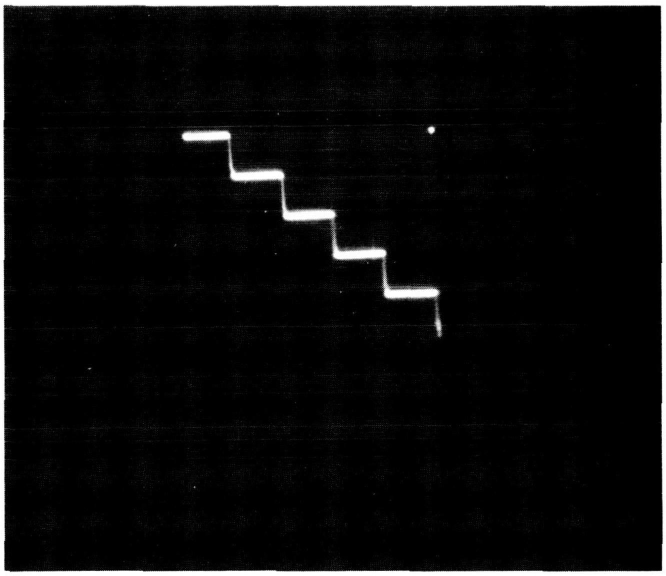


Fig. 50. Grey-Scale Simulated Video Signal

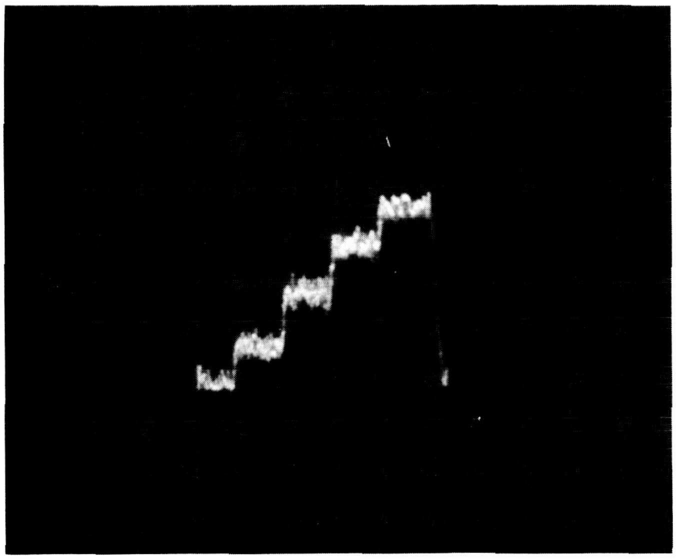


Fig. 51. Ground Tape Recorder Output for Simulated Video Signal